Feasibility of a floating GreenBattery

Concept design for the GreenBattery on the energy storage lake of the Delta21 project

J.W. van der Blonk

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by

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Abstract

The use of renewable energy sources like solar and wind energy for the generation of electricity are expected to increase in the coming decades. However, these sources are intermittent. Therefore Electrical Energy Storage (EES) systems are needed in the near future to assure a reliable electricity supply. These systems should also be able to deliver power in longer periods of time with low generation from wind and solar energy sources.

An example of such an EES system is the GreenBattery, developed by AquaBattery. This is a flow battery that stores the electricity by splitting salt water in an acid and a base. Because the main component of the GreenBattery is salt water, this battery is safe in use, as it can not catch fire or explode. Furthermore, this makes the battery environmentally benign and cost competitive with other EES systems.

The main focus of this thesis is to make a concept design of a GreenBattery that can be placed on a water like a lake. This concept is evaluated in a case study regarding the energy storage lake of the Delta21 project. This battery could provide a reliable backup electricity source for e.g. the Port of Rotterdam or stabilise the electricity output of renewable sources. Therefore, the main research question of this thesis is: ‘How can AquaBattery’s GreenBattery be realised on the energy storage lake of the Delta21 project, providing long term storage?’

To answer this question, first the design basis is explored. Based on this, concepts are generated using a morphological chart method and the most feasible concept is chosen using a multi-criteria analysis. This chosen concept is worked out in more detail, after which its technical and economic feasibility are investigated.

The most feasible concept turned out to be a floating concept. This concept uses floating rigid tanks to store the different liquids present in the GreenBattery. The power unit, where the electricity conversion takes place, is placed on top of these tanks. Furthermore, the feasibility of integrating a solar photovoltaic system on the floating tanks is investigated, because of the large area available for multiuse on such an island. The resulting dimensions of the floating tanks is 98 by 98 by 3 m (length, width, draft). Four of these tanks can be coupled together to form one floating island. Such an island can store about 560 - 800 MWh of energy, depending on the required storage duration and about 3.2 MW_p of solar panels can be placed on top of the tanks. In total, about 300 of such islands can be placed on the energy storage lake of the Delta21 project. Such an island is technically feasible, because the natural periods are larger than the expected wave periods. Therefore, the motions and forces of the island will be minimal. Furthermore, in terms of costs, the floating GreenBattery is cost competitive with other EES systems and therefore will be economically feasible as well.

Preface

In this thesis, I propose a concept design for a floating GreenBattery on the energy storage lake of Delta21. This concept could help the integration of renewable energy in the energy production, by stabilising the electricity output of renewable energy sources. I wrote this thesis as a report of my graduation project for the master Offshore and Dredging Engineering at the TU Delft, with the support of AquaBattery, the company developing the GreenBattery.

During my studies, my interest for floating structures and their interaction with waves has been aroused more and more. Although this thesis had its tough periods, it also was an interesting opportunity to discover more of this world and the complexity of engineering.

I would like to thank anyone who has helped me during this project, whether it was more technical or more mental support. With your help, I was able to bring this project to a good end. Sebastian Schreier, supervisor from the TU Delft, thank you a lot for all the hours you spent to discuss my findings. You always asked thousands of questions to push me further and help me substantiate the choices I made. Alex Sow, daily supervisor form AquaBattery, thank you for always making time to think with me. Your positive view on this project encouraged me in difficult times. Jiajun Cen, supervisor from AquaBattery, if I got stuck, you always knew what to do and how to go on with the project, thank you. Huub Lavooij and Leen Berke from Delta21, thank you for bringing me in contact with AquaBattery and for your advise during the project. Furthermore, I would like to thank the members of the graduation committee for their time and effort.

I would like to thank my family and friends for all their support and for always believing in me. A special thanks goes to my lovely wife Willemijn, who always motivated me and believed in me. Finally, I want to thank God for His help every day.

Contents

List of abbreviations

CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CF	Capacity Factor
COB	Centre Of Buoyancy
CRF	Capital Recovery Factor
DoF	Degree of Freedom
EES	Electrical Energy Storage
EoM	Equation of Motion
ESL	Energy Storage Lake
HES	Hydrogen Energy Storage
LCC	Life Cycle Costs
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost Of Storage
MC	Morphological Chart
MCA	Multi-Criteria Analysis
NAP	Normaal Amsterdams Peil
OPEX	Operating Expenditure
PHS	Pumped Hydro Storage
PU	Power Unit
PV	Photovoltaic
RAO	Response Amplitude Operator
RES	Renewable Energy Sources
SA	Sensitivity Analysis
SAM	Stiffness Approximation Method
TSO	Transmission System Operator
VLFS	Very Large Floating Structures
VRFB	Vanadium Redox Flow Battery

1 Introduction

In recent years, the contribution of Renewable Energy Sources (RESs) like solar and wind to the total electricity production has increased [8, 53] to decrease the reliability on fossil fuels, and this trend will continue. Atradius [8] expects the worldwide contribution of RESs to the total energy production to be 40% by 2040 in their New Policies Scenario. In their Sustainable Development Scenario, RESs even become the dominant energy source. BloombergNEF [10] expects that RESs supply 90% of the European electricity market by 2040.

This growth will mainly be realised by installing new wind turbines and solar photovoltaic (PV) farms [10], because government support is highly deviated towards these types of RESs [8]. BloombergNEF [10] expects that 80% of the European renewable energy will be supplied by solar and wind energy in 2040.

A characteristic of these electricity sources is that they are intermittent; they only produce electricity when their source is available. However, the current grid is based on electricity producers that produce electricity when there is a demand [28] and is not made to handle many small point sources of electricity generation. This creates a problem, because the availability of RESs does not always meet the demand for electricity. For expample, solar PV systems have their maximum energy output around mid-day, while households normally demand the highest amount of energy in the early morning and evening. With a high penetration of intermittent RESs, this might lead to grid congestion, because the generated electricity is not used [28]. This is a problem for Transmission System Operators (TSOs) who are responsible for matching supply and demand of electricity.

There are several solutions to this problem described in literature [10, 28, 68, 78]. First, a part of the demand can be adjusted to the availability of electricity. E.g. electric vehicles can sometimes be charged when there is enough electricity available. Second, the electricity generated by intermittent RESs can be stored until there is a demand using an Electrical Energy Storage (EES) system. Third, flexible and fast responding electricity sources, like the current gas turbines, can be used to accompany the intermittent RESs. Fourth, the international grids can be extended to exchange renewable energy between countries. Fifth, curtailment can be used in cases where there is a surplus of electricity. Sixth, a better forecasting of the renewable energy production will make it easier to respond to changes in electricity production. All these solutions will be needed to create a solution to the intermittency problem of RESs. According to BloombergNEF [10], EES will be one of the most important solutions, because

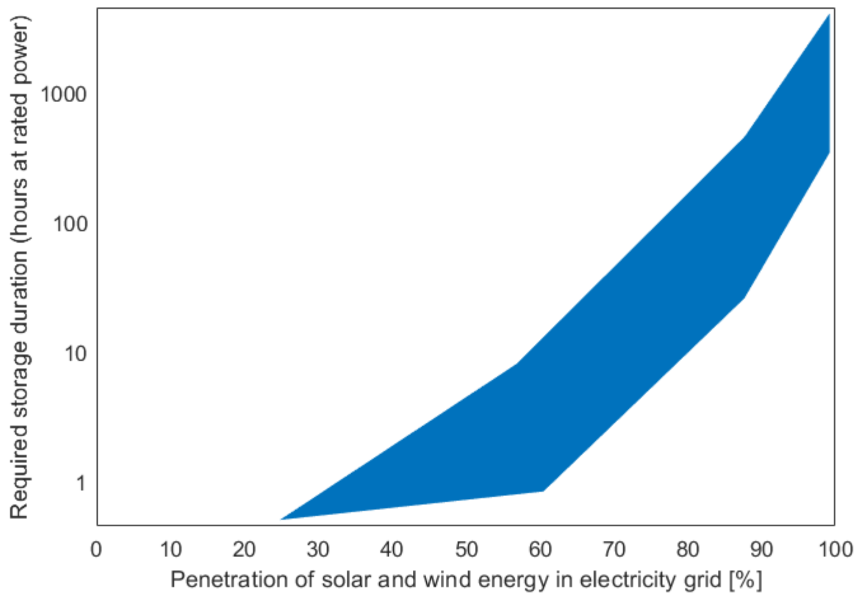


Figure 1.1: Required storage duration versus the penetration of solar and wind energy in the electricity grid [4]

of its ability to decouple the moment energy is generated and the moment energy is used. Therefore, this thesis aims to contribute to the realisation of EES systems.

These EES systems should be able to level out the fluctuations in electricity generation with various periods. However, in a society with an increasing share of RESs in the electricity grid, the main demand is EES systems that can provide longer term storage, like seasonal storage [4, 47, 74]. These storage media can deliver energy during e.g. cloudy and windless periods of multiple days up to weeks, so called Dunkelflautes [27].

Albertus et al. [4] presented the required storage duration (hours a storage medium can deliver energy at rated power) as a function of the penetration of wind and solar energy in the electricity grid, see fig. 1.1. From this figure, it can be concluded that a storage duration of about 10 to 100 hours is needed with a penetration of solar and wind energy in the electricity grid of about 70% to 90% [4], which is expected to be the case in Europe by 2040 [10]. These EES systems should have a power capacity of in total about 100 GW in the EU [18]. For comparison, the currently installed capacity of the electricity generators installed in the EU is almost 1000 GW [40]

DNV-GL [97] did research to the need for energy storage to generate a constant energy supply in the Netherlands, based on the 'ENTSO-E visie 3' scenario. This scenario assumes 6 GW onshore wind, 6.8 GW offshore wind and 9.1 GW solar PV in the Netherlands by 2030 [97]. The estimated need for storage capacity versus the storage duration (the time an EES system can produce electricity at rated power) is given in fig. 1.2. From this figure, it can be seen that a storage capacity of about 16 GWh is needed with a storage duration of about 10 h, while a storage capacity of about 130 GWh is needed with a storage duration of 100 hours.

1.1. Energy storage systems

The EES systems that can generate these required storage capacities are described in many studies [1, 48, 73, 76, 85, 106]. EES systems with a storage duration of at least one hour include battery energy storage as well as mechanical and chemical storage systems. Examples of battery energy storage

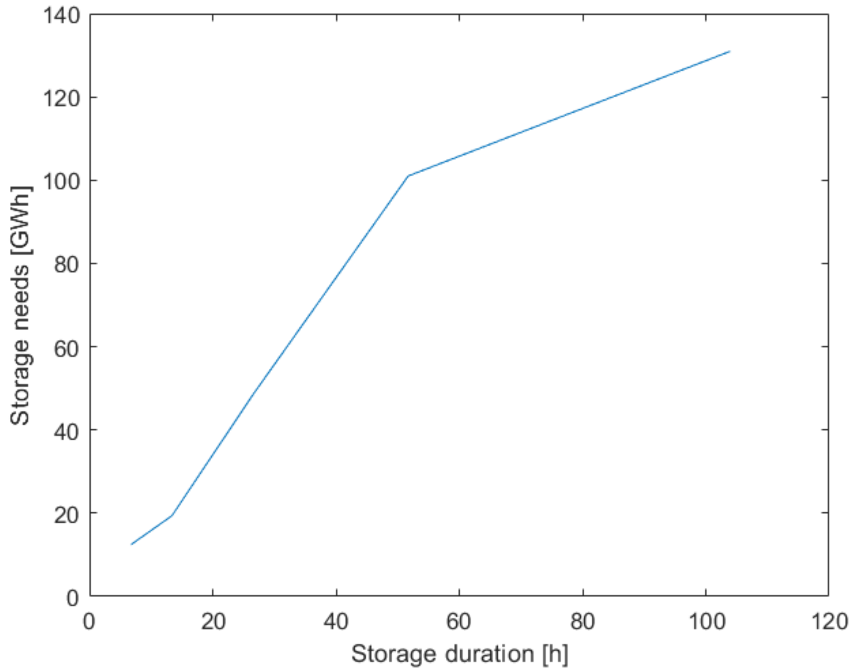


Figure 1.2: Need for energy storage in 2030 versus storage duration based on the ENTSO-E V3 scenario [97]

systems are the lead-acid battery, lithium-ion battery and Vanadium Redox Flow Battery (VRFB). Mechanical storage systems are e.g. Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES). The probably best known chemical storage system is Hydrogen Energy Storage (HES).

Battery energy storage systems are normally made with a storage duration up to several hours. They have a large efficiency, in the case of a lithium-ion battery almost 100%. However, mainly from an environmental point of view, they have their disadvantages. Lead-acid batteries contain large amounts of lead, which is toxic when spilled in the environment [98]. Lithium-ion batteries can catch fire or explode and contain scarce materials [98]. The vanadium used in VRFBs is a heavy metal and can be dangerous if it leaks into the environment [32, 98].

Mechanical storage systems often have a larger storage duration than chemical batteries. In case of PHS, energy is stored in pumping water from a low reservoir to a higher reservoir. Most times both reservoirs are lakes. Another possibility is to store energy in large tanks filled with seawater, which are placed on the bottom of deep waters like oceans [82, 87]. When the tanks are emptied, a vacuum is created and in that way energy is stored. In case of CAES, energy is stored in compressing air. The compressed air is stored in high pressure tanks or underground salt caverns. Cazzaniga et al. [17] proposed to use the cylindrical floaters of a floating solar farm to store the compressed air. However, the application of most mechanical storage systems is location dependent.

In HESs, the electricity in stored in hydrogen. This hydrogen can be stored in e.g. underground salt caverns or transported to a place where energy is needed. However, HES currently has a rather low efficiency of about 20-50% [73], wich means that at least half of the electricity is 'thrown away'.

Table 1.1 gives an overview of the characteristics of different EES systems. From this table, it can be seen that the energy storage systems that are suitable for the intended storage duration of 10 - 100 hours are PHS, CAES, HES and the GreenBattery.

Table 1.1: Overview of different EES systems. Data for PHS up to HES from [73], for GreenBattery from AquaBattery. PHS: Pumped Hydro Storage, CAES: Compressed Air Energy Storage, VRFB: Vanadium Redox Flow Battery, HES: Hydrogen Energy Storage

Energy storage technology	Power density [kW/m³]	Energy density [kWh/m³]	Power capital costs [$/kW]	Energy capital costs [$/kWh]	Efficiency [%]	Storage duration
PHS	0.01-0.12	0.133-0.5	600-2000	5-100	70-85	1-24h
CAES	0.04-10	0.4-20	400-800	2-50	42-54	1-24h
Lead-acid	10-400	25-90	300-600	200-400	85-90	secs-hrs
Lithium-ion	56-800	94-500	1200-4000	600-2500	~ 100	mins-hrs
VRFB	2.5-33.4	10-33	600-1500	150-1000	85	secs-10h
HES	1-300	25-770	500	15	20-50	secs-24h
GreenBattery	5	3	1500	50	80	hrs-days

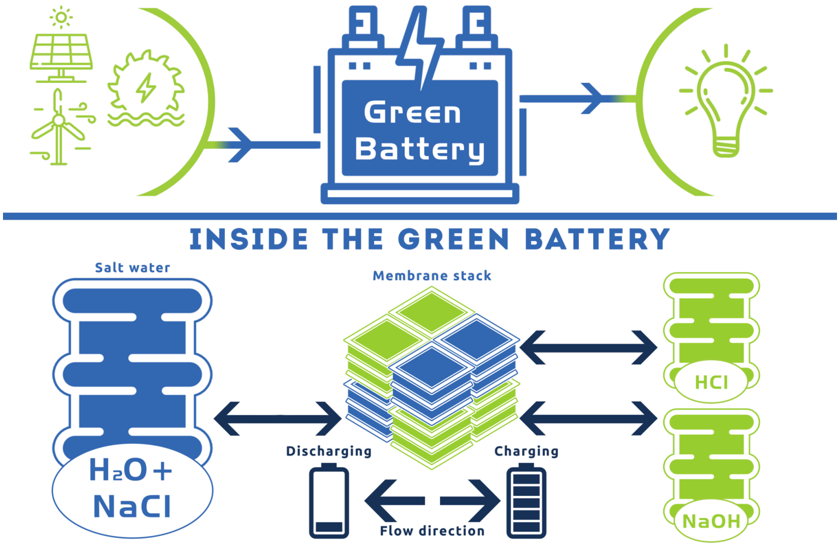


Figure 1.3: Working principle of the GreenBattery [6]

1.2. GreenBattery

This GreenBattery is a relatively new EES system developed by the Dutch company AquaBattery. The working principle of this battery is based on the blue energy principle, energy generation and storage using electrodialysis and reverse electrodialysis [77, 81, 98]. In this battery, salt water is separated in an acidic and a basic water by means of ion exchange membranes and electricity. When this process is reversed, the acidic and basic water is converted back to salt water via the membrane stacks and the electricity is released. This is schematically presented in fig. 1.3.

The GreenBattery consists of three main components. Tanks are used to store the liquids. A power unit (PU), where the ion exchange membranes are located, is needed for the electricity conversion. Furthermore, auxiliaries like pumps and pipes to transport the liquids are needed. Because the tanks and PU are separate components, they can be sized independently. This brings the advantage that the storage duration can be sized to the wishes of a client.

Regarding the technical characteristics, the energy density of the GreenBattery can best be compared to PHS with a height difference of 800m; the energy density is currently around 3kWh/m^3. The efficiency of the GreenBattery is currently around 60%, but the GreenBattery is still under development. In the end, AquaBattery expects that the efficiency will be around 80%. The energy capital costs of the GreenBattery are expected to be about 50 €/kWh, while the power capital cost are expected to be about 1500 €/kW.

The main advantage of the GreenBattery compared to other batteries, is the fact that the GreenBattery does not contain toxic chemicals and is therefore environmentally benign. Next to that, the GreenBattery is safe in use, because no chemical reactions that can cause a fire or explosion are needed. Furthermore, the GreenBattery is more cost effective, mainly regarding the energy capital costs. Especially for a battery with a larger storage duration, this is beneficial.

Compared to mechanical storage systems, the costs of the GreenBattery are similar. However, mechanical storage systems are often location dependent, due to the dependence on differences in height or the presence of salt caverns. Next to that, the GreenBattery has a higher energy density, which means that using the same land space, more energy could be stored.

Although HES has lower costs compared to the GreenBattery, the efficiency of the GreenBattery is higher. This means that when using HES, more wind turbines and solar panels need to be build, to deliver the same amount of electricity.

However, one of the main disadvantages of EES systems, including the GreenBattery, is their relatively low energy density compared to fossil fuels. For example, the energy density of coal is 6.3 - 9.4 MWh/m^3 [66], while the energy density of Lithium-ion batteries is 94 - 500 kWh/m^3 [73]. Therefore, for storing the same amount of energy, more space is required when using the sustainable EES systems.

1.3. Delta21

One example of a project about creating extra space for energy storage in the Netherlands is the Delta21 project. In this project, a lake will be created southwest of the 2nd Maasvlakte in the Netherlands, which will be used for energy storage using a PHS system.

The main goal of this Delta21 project is to increase the water safety in the Rhine-Meuse Delta. Due to an increasing sea level, radical dike reinforcements are needed in this region to assure water safety during a high sea level and a high river discharge. However, this would be a very expensive operation. Therefore, Delta21 is developing a more cost effective alternative. Their plan is to build a new dike at the west side of the Haringvliet, with pumps that can pump the water out of the Haringvliet in case of a high sea level and high river discharges [65].

However, in this scenario, the pumps would function only once in 5-10 years, which would cause a high failure probability [65]. Therefore, Delta21 want to multiuse the pumps for energy storage in an Energy Storage Lake (ESL), that should be created southwest of the second Maasvlakte, when they are not needed for water safety. The pumps have a total capacity of 1.8 GW and the lake will be used for energy storage on a day/night shift (storage duration of about 12 h) [65].

The location and lay-out of this lake are depicted in fig. 1.4. The pumps used for the water safety and energy storage are located at the south-west side of the lake. In the dam between the Haringvliet and the lake a siphon is located that can be used to discharge the river water in the ESL in case the tidal in- and outlet of the Haringvliet is closed.

Delta21 is interested in the possibilities for multiuse at this lake. One of the possibilities for multiuse they are interested in is placing another EES system, preferably combined with a solar PV system, on the ESL. In case of a combination with a solar PV system, the electricity generated by the solar panels could be stored directly in the EES system in case of an surplus of electricity.

The GreenBattery would perfectly fit on this lake, because it mainly consists of salt water. Since the lake consists of salt water as well, this means that even in the case of a leak, the environment would

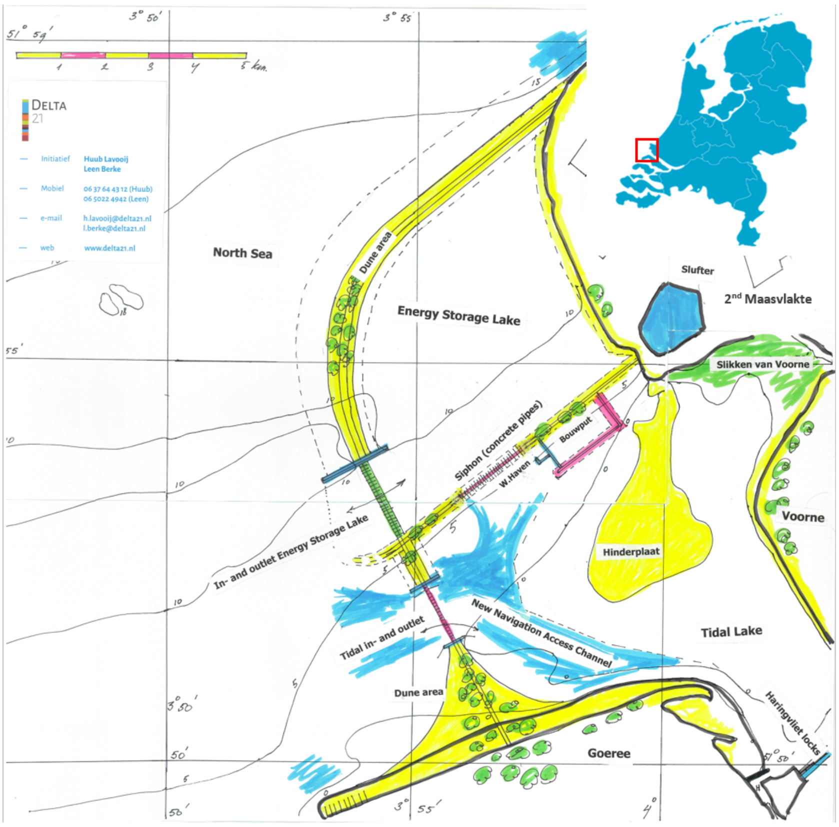


Figure 1.4: Location and layout of the energy storage lake. Figure from Delta21 (H. Lavooij, personal communication, April 29, 2020) and [22]

not be damaged. Even if the acid or base would leak, it could be neutralised using the other. Next to that, it is possible to combine the GreenBattery with a solar PV system.This GreenBattery should have a storage capacity that is at least in the same order of magnitude as the ESL, namely multiple GWh, because otherwise it would not really add value. The storage duration should be between 10 and 100 h, as stated in fig. 1.1. Most likely, the final storage duration will be closer to 100 h, to complement the ESL.

Placing such a GreenBattery on the ESL gives a number of advantages, next to the normal use of an EES system to trade with electricity. First, it could deliver energy to the pumps in the ESL in storm conditions, when the pumps are used for the water safety. Second, it could be used as a backup electricity source for the port of Rotterdam or the region Rotterdam. A third option is to combine this battery with e.g. a hydrogen production facility. In this case, the battery could be used to smooth out the production of intermittent renewables and ensure a stable electricity supply for the production of green hydrogen. Another benefit is that the battery can store renewable energy that would otherwise have been curtailed. In this way, less wind turbines or solar panels are needed to generate the same amount of renewable energy. Furthermore, the GreenBattery could be combined with aquaculture to produce seafood like oysters and mussels.

1.4. Review of floating structures

However, AquaBattery has not yet developed a structure that enables the GreenBattery to be placed on a lake or another kind of water. Therefore, the main focus of this thesis is to investigate how the GreenBattery of AquaBattery can be placed on the energy storage lake of the Delta21 project, providing long term storage.

In scientific literature, there already exists a myriad of large floating or submerged platforms that could be used to house the GreenBattery. Those include floating solar PV structures, Very Large Floating Structures (VLFS) and submerged or floating storage tanks.

Düzenli et al. [35], Sahu et al. [86] and Trapani and Redón Santafé [96] reviewed floating solar PV systems. From these reviews it can be seen that those systems are most times kept afloat using rigid pontoons type structures with the solar panels mounted on top. New designs sometimes use submerged solar panels to decrease wave loads like Rosa-Clot et al. [84] proposed or flexible floating solar panels which are more compliant to the waves like Trapani and Millar [95] did.

Lamas-Pardo et al. [64] gave an overview of the different types of VLFS currently being considered in literature. Those VLFS consist of modules, based on different kinds of offshore structures, that are connected together to form one large floating island. Such an island can be used for multiple purposes like floating airports and towns.

Of course, the GreenBattery could directly be placed on such a floating structure. However, it could be more beneficial to combine the floating structure and the GreenBattery in one. For example, the liquids can be stored in tanks placed on a floating structure, but it might be more cost effective if the tanks form the floating structure itself.

For this purpose, multiple solutions have been introduced over the years. Hawthorne [50] introduced the flexible barge for the transportation of oil over water. Next to that, rigid tanks are used for floating oil storage [25]. Furthermore, there are several patents for submerged storage tanks like [19, 23], along with storage bags for under water CAES [80]. Last, several structures are designed for buoyancy energy storage systems [9, 60] of which components could be used for a GreenBattery on a water.

In short, it can be stated that there are several possibilities and components that can be used to make a concept design of a GreenBattery that can be placed on water. However, in current scientific literature, it is not yet described what kind of concept will be most feasible to enable the GreenBattery to be placed on water. This thesis tries to fill this knowledge gap.

1.5. Research questions and approach

The main research question of this thesis is: 'How can AquaBattery's GreenBattery be realised on the ESL of the Delta21 project, such that it can provide long term storage?' To answer this question, multiple sub-questions are formulated:

1. What is the most feasible concept design for this design problem?
2. What is a suitable layout of this concept design for a GreenBattery in the ESL of Delta21?
3. How feasible is the overall concept from a technical point of view?
4. How does the cost of this concept compare to other EES systems?

With answering these research questions, this thesis contributes to the following Sustainable Development Goals:

- SDG 7. Affordable and clean energy, because the battery system creates a means of storage to help the energy transition.
- SDG 8. Decent work and economic growth, because in this way sustainable economic growth is promoted.

- SDG 9. Industry, innovation and infrastructure, because this makes sustainable industrialisation possible.
- SDG 11. Sustainable cities and communities, because the GreenBattery can help cities to make the energy transition.
- SDG 14. Life below water, because waters are used for sustainable development.

In this thesis report, the answers to the research questions are given. Each question is answered in a separate chapter.

In chapter 2 the design basis is composed by first giving the results of a short stakeholder analysis. After this, the ESL of the Delta21 project and the GreenBattery are described in more detail. The chapter is closed with a description of the design objectives and requirements for this concept design, based on the stakeholder analysis.

Chapter 3 answers the first research question, by investigating the most feasible concept to solve this design problem. First, the possible sub-solutions are analysed using a morphological chart method. After this, ten concepts are generated using the described sub-solutions. Finally, those concepts are compared to each other in a multi-criteria analysis based on the design objectives and requirements to identify the most feasible concept.

This concept is worked out in more detail in chapter 4. First, more detailed requirements are set up, which should be obeyed by the detailed design. Based on these requirements, a suitable layout of the chosen concept is investigated. In this way, the third research question is answered.

The technical feasibility of the chosen concept, research question four, is described in chapter 5. In this chapter, the most important response is determined first. After this, the hydrodynamic response is investigated using analytical hydrodynamic calculations. A design iteration based on the results of the hydrodynamic analysis is proposed.

Chapter 6 answers the fifth research question by analysing the economic feasibility of the concept. First, the costs of one island are determined. After that, the costs of this concept are compared to other EES systems, to investigate the economic competitiveness. Next, the benefits using energy arbitrage are estimated. Based on these results, measures to reduce the costs are proposed. Last, the added value of the combination with a solar PV system is described.

Finally, the conclusions of this thesis are given in chapter 7. In this chapter, the answer to the main research question is given by summarising the conclusions to the different research questions.

2
Design basis

The goal of the design basis is to make clear what the problem is about. With a clear description of the design basis, a good solution can be generated. First, the stakeholders were identified. Second, the location was analysed. Third, the GreenBattery is described. Fourth, the design objectives of this study were investigated. And fifth, the requirements set to the concept were analysed.

2.1. Stakeholders

A stakeholder analysis was performed to identify the stakeholders of this project and their needs [12]. First, the most important stakeholders were identified by brainstorming and in discussions with colleagues. After that, the most important objectives of these stakeholders were identified by directly asking them and searching in literature. The results of this analysis are presented in table 2.1.

One of the most important stakeholders is the final customer that will operate the GreenBattery. However, this customer is not known yet. Potential customers include TSOs, like TenneT, and operators of wind or solar farms. TSOs could use this battery for grid stability, while operators of wind or solar farms could temporarily store their electricity in this battery and sell it when the electricity price is higher. However, for TSOs it is under the current Dutch law not possible to operate an EES system [38], but since it is their responsibility to match the supply and demand of electricity, they might be interested in operating EES system.

The most important requirements from the operator will be in terms of the storage duration and rated power. As shown in chapter 1, the required storage duration will be between 10 and 100 hours by 2040. Therefore, it is assumed that the requirements of the final operator with respect to the storage duration lie in between these numbers. The final concept is made modular, so that it can be adjusted to the wishes of the operator. However, it is assumed that the GreenBattery on the ESL is used for large scale energy storage like the ESL, with a storage capacity in the GWh scale, to have a capacity at least in the same order as the ESL.

2.2. Energy Storage Lake

The concept design that is being developed in this thesis will be placed on the ESL of Delta21. Therefore, the conditions present at this lake are analysed and presented in this section. The final concept

Table 2.1: Stakeholder analysis

Stakeholder	Most important objectives for this project
AquaBattery	Technically feasible; Economically achievable (Sell the GreenBattery); Comply with regulations; Scalable concept
Delta21	Economically achievable; Maximize energy output of ESL (preferably with solar panels); Not obstruct other functions; No negative influence on nature; Part of sustainable energy hub
Operator	Storage duration 10-100 hours; Storage capacity in order of GWh; Modular system
Governments	Sustainable, Affordable and Reliable [33]; Comply with regulations
Environmental parties	No negative influence on nature

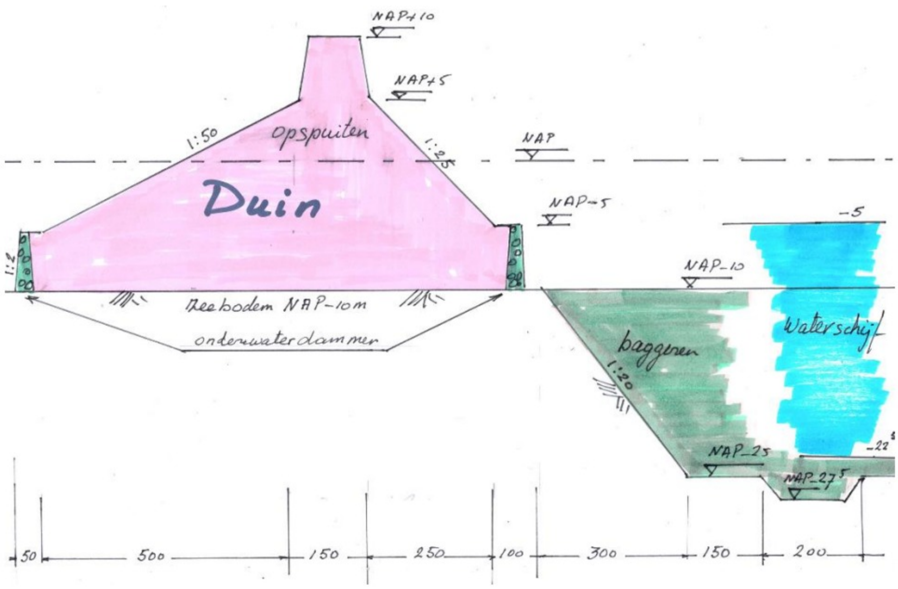


Figure 2.1: The dike system surrounding the ESL. The lake is filled up to max NAP -5 m and emptied to max NAP -22.5 m. Note, the bottom of the lake is at 27.5 m below NAP, not at 25 m Figure copied with permission from Delta21 [65]

must be able to survive in these conditions.

Due to the use of this lake as an ESL, the water level in the lake will have a large daily fluctuation. The water level in the lake will vary between 5 m below the Normaal Amsterdams Peil (NAP) and 22.5 m below NAP, thus the difference in water level between day and night will be 17.5 m. The bottom of the lake will be at 27.5 m below NAP, which leaves a minimum water depth of 5 m. The average area of the lake is about 24.7 km^2, while at low water (22.5 m below NAP), the surface area of the lake is about 22.9 km^2. The dike profile is depicted in fig. 2.1.

The environmental conditions at the ESL are summarised in table 2.2. In this table, first, the maximum wind and wave conditions are described. They are based on the 100-year storm, because according to Vugts [103], an offshore structure must be able to survive such a storm. Next to that, the predominant wind and wave conditions are included in the table, because they provide insight in the regular conditions at the ESL. Furthermore, the air and seawater temperature ranges and the soil conditions are given. More information on the wind and wave conditions can be found in appendix A.

Table 2.2: The environmental conditions at the ESL

Condition	Value	Note
100-year wind speed at 10m above ground	U_{10} = 31 m/s	Data obtained from waveclimate.com [107] and Infoplaza (P. Groenewoud, personal communication, May 5, 2020)
Predominant wind speed at 10m above ground	Direction: south-west. Magnitude: U_{10} = 5 - 7 m/s	Data obtained from waveclimate.com [107] at location 52°00' N, 03°40' E
100-year wave conditions	Significant wave height: H_{m0} = 0.8 - 1.6 m. Peak period: T_p = 2.7 - 4.2 s	Calculated using the equations described by Holthuijsen [51] and Young and Verhagen [109]
Predominant wave conditions	Significant wave height: H_{m0} = 0.14 - 0.32 m. Peak period: T_p = 1.4 - 2.1 s	Calculated in the same manner as the maximum wave conditions, see also appendix A
Maximum current	U_c = 1.33 m/s close to the pumps. U_c = 0.94 m/s at 1000 m from the pumps	According to estimations of Delta21 [26]
Air temperature range	Ranging from -13 °C to 38.9 °C	Minimum and maximum temperature measured during the past 50 years at Hoek van Holland according to KNMI [61]
Seawater temperature	Average yearly minimum: 5.6 °C. Average yearly maximum: 18.8 °C	Data obtained from climatedata.org [21]
Soil conditions	Sand from seabed until NAP -50 m; clay until NAP -60 m; sand below NAP -60 m	Data obtained from Delta21 (H. Lavooij, personal communication, May 7, 2020). Data is in accordance with measurements BS031271 and BS031367 from Dinoloket.nl [30]

Table 2.3: Components of the GreenBattery and what must be determined

Component:	What can be changed:
Tanks	New design allowed
Power unit	Housing
Auxiliaries	Housing
Pipes	Type of pipe
Solar panels	Location
Anchor	Choosing type of mooring system
Connections	Choosing type of connection
Grid connection	High level
Connect PU and PV	High level

2.3. GreenBattery

This section describes the components and functions of a GreenBattery for the ESL of Delta21. In table 2.3 the components of a regular GreenBattery are presented, including what can be changed about the components in the new design.

The functions of the GreenBattery on the ESL were stated by analysing the required components for a GreenBattery on water and describing the functions of these components. Later, this set of functions was checked in a brainstorm session with colleagues on completeness, after which the functions were ordered in higher and lower level functions. The final set of functions is depicted in a function tree, see fig. 2.2.

The main function of the system is defined as 'House the GreenBattery on water', because that is what the concept design should be able to do. This main function is split up in three sub-functions. The system must be able to house the components of the GreenBattery, keep the GreenBattery in place and connect the GreenBattery to the electricity grid. The final functions of the GreenBattery are categorised according to these three sub-functions.

2.4. Objectives

To clarify the objectives, the 'objectives tree method' described by Cross [24] and Jones [55] was used. To get a complete list of design objectives, first a brainstorm session was organised with a colleague of AquaBattery. Next to that, the outcome of the stakeholder analysis was used. Finally, the list of design objectives was checked using the aspects covered in the PESTEL framework [3], which stands for Political, Economic, Social, Technological, Legal and Environmental, to ensure that a complete list of objectives was generated.

The objectives are presented in a sideways tree structure in fig. 2.3. At the left-hand side of the figure the main objective is given. This objective was split up in different sub-objectives, which are placed at the right-hand side of the main objective. The most detailed objectives are called the 'leaves' of the objectives tree and are placed at the left-hand side of the objectives tree.

The main goal of this thesis is to develop a concept design that enables the GreenBattery to be placed on water (the ESL). Therefore, this has been chosen as the overall design objective. This goal was split into the following categories: the concept must satisfy the economic design objectives, the concept must satisfy the technical design objectives and the concept must satisfy the societal design objectives.

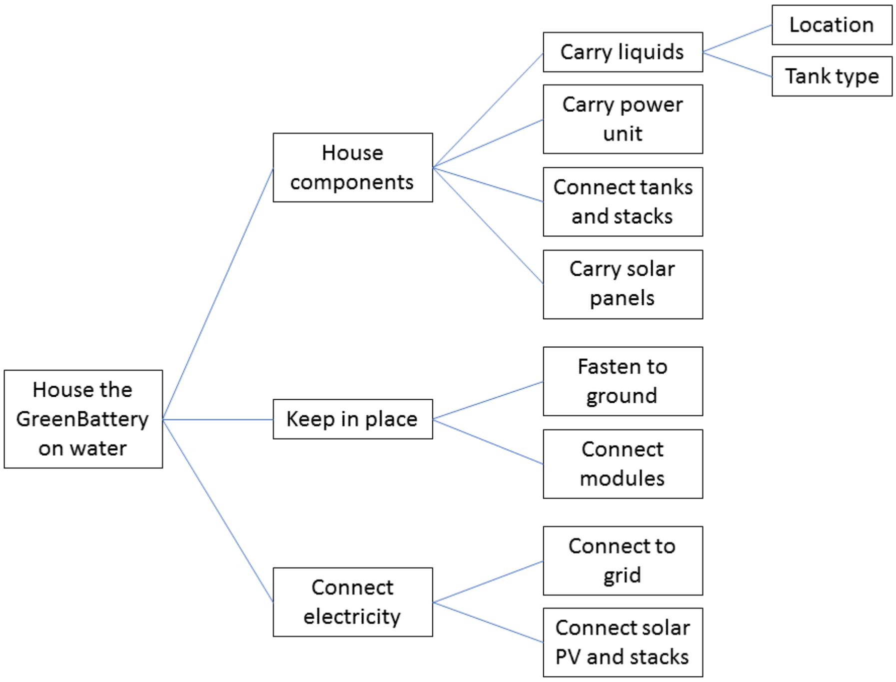


Figure 2.2: The function tree for the GreenBattery on water

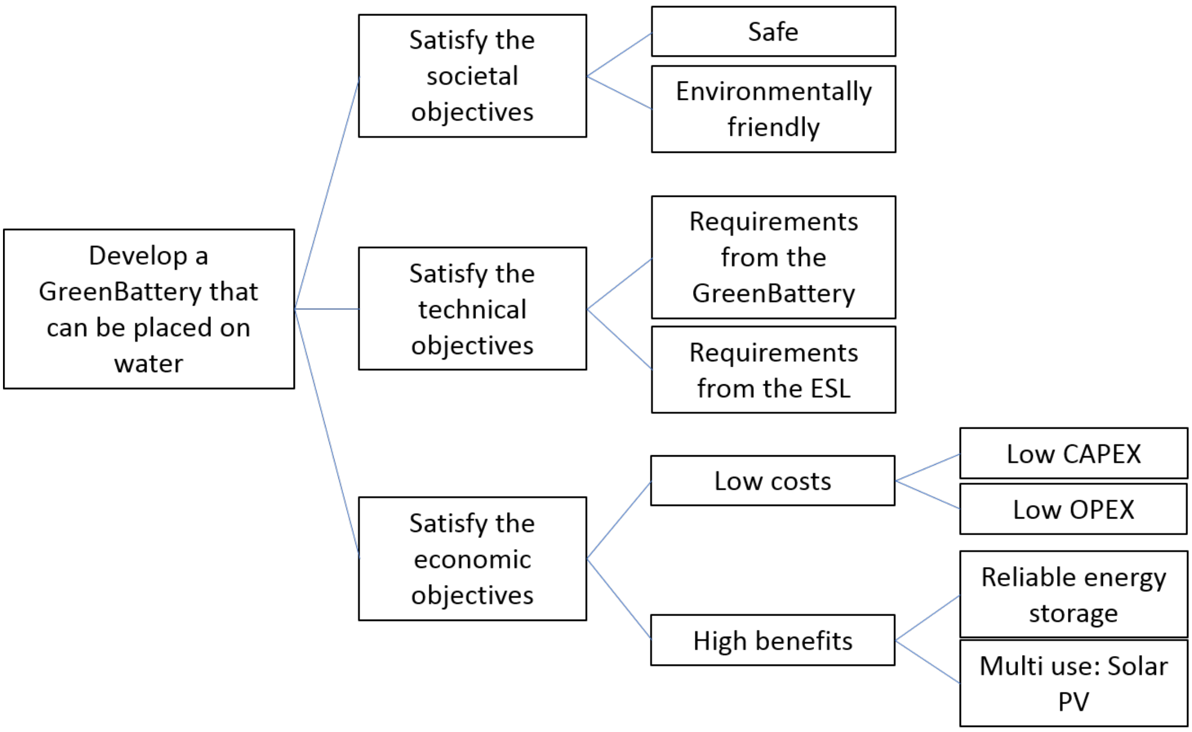


Figure 2.3: The objectives tree for the GreenBattery on water

Economic objectives
From an economic point of view, it is most important that the GreenBattery has a low Levelised Cost Of Storage (LCOS). The LCOS is calculated by dividing the total costs over the lifetime of a EES system by the electricity sold back to the grid during its lifetime. This ratio indicates the cost competitiveness of the battery system [57]. Currently, the LCOS of most EES systems is beteen 0.05 and 0.20 €/kWh [110]. So, in order to achieve a cost competitive battery system, the costs of the system should be as low as possible to be cost competitive. Next to that, the benefits created by the system should be as high as possible.

The costs of the system are mainly determined by the capital expenditure (CAPEX) and the operating expenditure (OPEX). Both should be as low as possible to achieve the objective of a low cost system. It could be that a reduction in the one leads to a increase in the other. Therefore, it is important to take both into account.

The benefits are mainly determined by the characteristics of the GreenBattery itself. However, it is also influenced by the reliability of the system. Next to that, the benefits could be positively influenced if the system would be multifunctional [43, 68]. In this case, adding a solar PV system would be easiest and is also requested by Delta21, see table 2.1. Next to that, solar PV is a renewable energy source, which contributes to the sustainability of the Delta21 project. Therefore, the objective ‘High benefits’ was split into ‘multi use: Solar PV’ and ‘Reliable energy storage’. Another factor that could lead to an increase in the benefits is the efficiency. However, the goal of this thesis is not to improve the GreenBattery, but to place it in a different environment.

Technical objectives
The first aspect covered in the technical objectives is that the system should be able to survive in all environmental conditions during its lifetime, e.g. storms and salt water. Therefore, the first technical objective is to meet the requirements from the environment.

Second, the system must house the GreenBattery. Therefore, it is important that the final concept satisfies the requirements of the GreenBattery. Those requirements come from e.g. the components and characteristics of the GreenBattery. One example of such a requirement is that the concept should not influence the efficiency. One way the concept influences the efficiency is by the required pump power to transport the fluids from the tanks to the membrane stacks and vice versa. If e.g. the distance between the tanks and the stacks is very large, this can negatively influence the efficiency. Another aspect influencing the efficiency could be motions of the PU. However, this has not been investigated yet.

Societal objectives
The societal objectives have been split up in two groups. First, the concept should be environment friendly to both the local environment, e.g. the flora and fauna in the ESL itself, and global environment, e.g. by using recyclable components. Second, the concept should be safe for the workers that install or maintain the system. Third, the system should not hinder other users. However, the last one is mainly dependent on the location where the system is deployed and not on the system itself. Therefore, by satisfying the first two sub-objectives, the system can satisfy the societal objectives.

2.5. Requirements

Now that it is clear who the stakeholders of the project are, what the objectives and functions of the design are and what the lake looks like where the GreenBattery must be deployed, the final set of design requirements can be listed.

The requirements were set up using the ‘Performance Specification Method’ described by Cross [24]. The ‘leaves’ of the objectives tree were used as the ‘performance attributes’, the characteristics of the design to which requirements must be set. This was done to provide a complete overview of the important aspects. Each of these attributes was specified by a couple of requirements. This was done using logical thinking, in consultation with colleagues and by searching in literature.

The economic and technical requirements are set up using logical thinking, in consultation with colleagues, using a Recommended Practice of DNV GL about energy storage [31] and the requirements mentioned by Jawahir et al. [54]. The requirements regarding the environmental conditions are established using the environmental conditions calculated in section 2.2.

The requirements from the GreenBattery are established in consultation with a colleague who designed the first pilot system of the GreenBattery. Due to possible internal leaks in the PU, the liquids in the GreenBattery need to be ‘reset’ at certain times. This is done by emptying the acid and base tanks in the salt water tanks and than making demineralised water again to fill the acid and base tanks.

The societal requirements are set up using the regulations that were found applicable to battery systems on water. The ‘Nationaal Consortium Zon Op Water’ has done research to the permissibility of floating PV modules in the Netherlands [89]. They also provided a tool to estimate the influence on the local environment in case of stagnant water [88]. However, the GreenBattery is more than only a floating solar park. Therefore, the ADN [99], containing the regulations for the transport of potentially dangerous liquids over water, was checked for regulations about transporting the acidic and basic liquids over water. It is assumed that these regulations will also hold for storing these liquids on water.

Regulations with respect to the safety of the workers only describe how the work should be performed. No regulations were found that influence the concept design, so no requirements to the safety can be set from a regulatory point of view. However, an employer is responsible for a safe working environment [41]. Therefore, the requirements with regard to safety were evaluated using logic and in consultation with colleagues.

The influence of the concept studied in this thesis on the local environment is mainly determined by two aspects. First, the larger the part of the water surface covered, the less sunlight and wind can reach the water. This could have a negative influence on the water quality [59, 88]. However, those studies assume that the water will not be refreshed. However, in the ESL about 80% of the water will be refreshed on a daily basis. Analysis by Kyozuka et al. [63] to the influence on the water quality of a floating platform of about 7km^2 in Tokyo Bay, where the water under the platform got refreshed, reported a negligible influence. It is assumed that this will also be the case for the ESL. However, more research should be done to confirm this assumption. Second, if the acidic or basic water is spilled in the ELS, this might have an influence on the acidity of the sea water in the lake. Therefore, the requirements for the environment friendliness manly focus on minimising this risk, by e.g. using small and double walled tanks. The influence of the concept studied in this thesis on the global environment is mainly determined by the use of environment friendly materials [54].

The final set of requirements is given in table 2.4. In this table, the requirements are arranged according to the branches and leaves of the objectives tree. Next to that, it is stated whether a requirement is a demand, i.e. it must be met by any concept, or a wish, i.e. fulfilment of that requirement would make a concept better. Finally, if applicable, the source of the requirement is denoted.

Table 2.4: Identified requirements for the GreenBattery on water

Branch	Leaf	Requirement	Demand/ Wish	Source
Societal	Safety	Low risk of drowning during activities	Wish	
		Little installation and maintenance work requiring manpower	Wish	
	Environmentally friendly	Small chance of leakage of acid/ base	Wish	[90]
		Small amount of acid/ base in one reservoir	Wish	[90]
		No discharging or leaching of materials in water	Demand	[90]
		Double-walled tanks for storing acid	Demand	[99]
		Use of environment friendly materials	Wish	[54]
Technical	GreenBattery	4 types of tanks needed (salt, acid, base and demineralized water)	Demand	
		Possibility to completely drain the tanks	Demand	
		Easy volume measurement	Wish	
		Easy conductivity measurement	Wish	
		Resistant against salt/ acid/ base	Demand	
		Not decrease efficiency	Wish	
		Easy adjustment of storage duration (at least between 10 and 100 h)	Wish	
		Modular system	Demand	
		Storage capacity in GWh scale		
	ESL	Resistant against high wind speeds (at least 31m/s)	Wish	
		Resistant against waves (at least $H_{m0} \approx 1.6$m)	Wish	
		Resistant against currents (at least 1m/s)	Wish	
		Deal with changing water depths (from NAP -5 to NAP -22.5)	Demand	
		Little horizontal space needed for anchoring	Wish	
		Deal with different temperatures (at least from -15°C to 40°C)	Wish	
		Least deterioration over time	Wish	[31]
		No interference with other functions of the ESL	Demand	[90]
Economic	CAPEX	Low component costs	Wish	
		Easy installation	Wish	[54]
		Good transportability	Wish	[31, 54]
	OPEX	Easy maintenance access	Wish	[31, 54]
		Little maintenance required	Wish	

	Lifetime of about 20 years	Demand	[46]
Reliability	Empty tanks easy in motions	Wish	
	Reliable components	Wish	
Combine with Solar PV	Cost effective combination with solar PV	Wish	

3

Concept generation and selection

Based on the problem description in chapter 2, a concept can be generated. This process is described in this chapter, first, the solution space is explored using a morphological chart. After that, one concept is chosen in a multi-criteria analysis.

3.1. Concept generation

The method to generate the concepts is described first. After this, the resulting concepts are depicted.

3.1.1. Method used to generate the concepts

To find solutions to a design problem, multiple design methods have been introduced. Three of the most commonly used methods are presented here. Zwicky [114] introduced the Morphological Chart (MC) method, which is one of the most well known methods to analyse the solution space in a structured manner [24]. Gordon [44] introduced Synectics to solve difficult design problems [55]. Altshuller [5] introduced TRIZ, also known as the theory of inventive problem solving, based on his observation that inventions are based on only a limited amount of patterns.

According to Jones [55], the aim of a MC is '[t]o widen the area of search for solutions to a design problem'. Regarding Synectics, this method aims to stimulate the brain to think of new solutions to difficult design problems [55]. TRIZ on the other hand is a helpful tool to solve conflicts in a design [29] and directly points out a number of technical solutions [52]. The aim of the current design study is to find a complete set of solutions to the problem. Therefore, the MC method as described by Jones [55] and Cross [24] is used to explore the solution space.

In the MC method, concepts are generated by first dividing the problem in the different functions the concept must fulfil. The next step is to collect all the solutions for those functions. These solutions should then be listed per function into one overview. The last step is to investigate the most logical combinations of one solution of every function, from which a complete concept can be made.

Here, the completeness of the MC is checked in different manners. First, patents were analysed that contain possible solutions for the different functions. After that, different brainstorm sessions were held with colleagues to include their ideas. Finally, the completeness of the chart was checked using the ACRREX method [11], where ACRREX stands for Abstracting, Categorizing, Reflecting, Reformulating

Table 3.1: Overview of morphological chart for the design of a GreenBattery on water. Note, complete morphological chart in appendix B

Function	Solution 1	Solution 2	Solution 3
Carry liquids (location)	On lake bottom	Floating	Above water
Carry liquids (tank type)	Flexible tank	Rigid tank	
Carry power unit	Floating	Onshore	Above water
Carry solar panels	On top of the GreenBattery	Separate system	No solar PV system

and Extending and can be a useful tool for stimulating creativity.

Using the morphological chart, different concepts were generated by combining one solution of every function to a concept. Those concepts were discussed with colleagues to see whether the most logical combinations were chosen.

3.1.2. Generated concepts

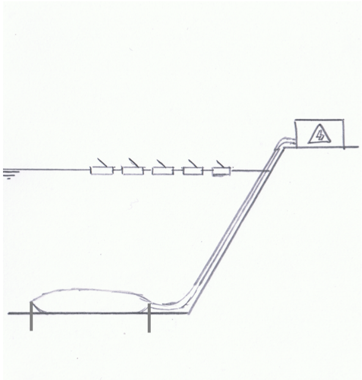
A short version of the resulting MC is given in table 3.1. The complete version is given in appendix B. To generate the solutions, the methods described in section 3.1.1 are used. For most functions, brainstorms with colleagues are used to come up with solutions, later checked using the ACRREX method. Regarding the function ‘Connect modules’, different patents of multi-body floating structures were analysed to find the common methods of connecting different floating bodies. Also, Koekoek [62] gives an overview of the different methods that can be used to couple floating structures. Regarding the function ‘Fasten to ground’, Rosa and Tina [83] sum up different mooring systems for floating PV farms.

The use of the ACRREX method is illustrated using the function ‘Fasten to ground’. Abstracting and categorising this function led to the definition: Connecting a point on the floater to a point at the fixed world. Reflecting, reformulating and extracting led to the following options:

- Fixed world point at seabed: direct mooring line to the seabed;
- Let the points overlap: this can be realised by connecting the floater to a fixed pile;
- Fixed world point at shore: mooring lines to shore;
- Fixed world point in water: pile to at half water depth and lines to the floater;
- Fixed world point in air: leads to same solution as fixed world point in water, only with the pile ending above water.

In this way the ACRREX method is used to check the morphological chart.

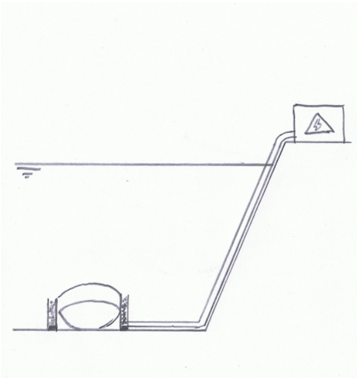
The ten concepts made using the MC are depicted in fig. 3.1. In concept 1 up to 4, the liquids are stored in underwater containers. Concept 1 and 2 use flexible underwater bags, while concept 3 and 4 use rigid underwater containers. The PU is located on land or on a bottom founded platform. These concepts can be combined with a separate floating PV system. Concepts 5 up to 10 store the liquids in floating storage tanks, with solar panels on top. For concept 5 up to 7, this is done using flexible floating bags. The PU is located at different places. Concepts 8 up to 10 use rigid storage tanks with the PU on top of the floaters. They are moored in different ways. Appendix B gives more detailed information on how the concepts are set up using the MC and which solutions are used in which concept.



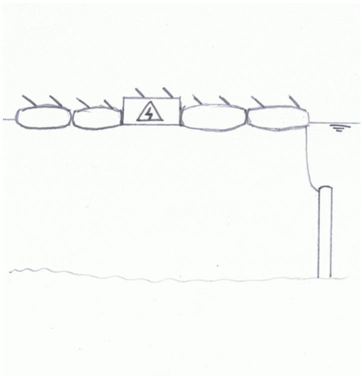
(a) Concept 1: Submerged flexible bags for storage and onshore PU

(b) Concept 2: Submerged flexible bags for storage and PU on bottom founded platform

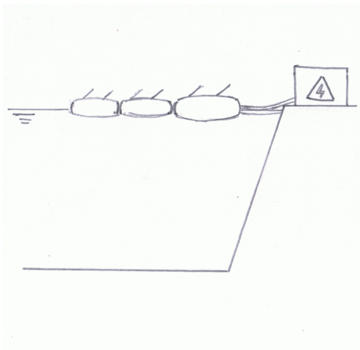
(c) Concept 3: Submerged rigid containers for storage and PU on bottom founded platform



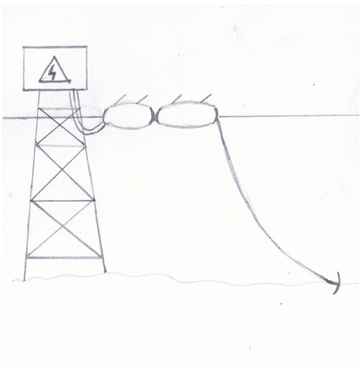
(d) Concept 4: Submerged rigid containers for storage and onshore PU



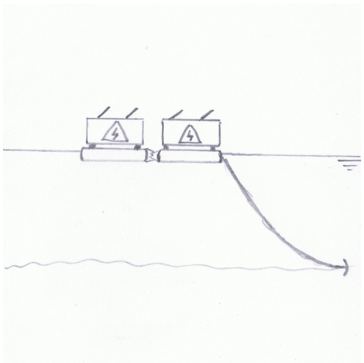
(e) Concept 5: Floating flexible bags for storage with solar panels on top and floating PU



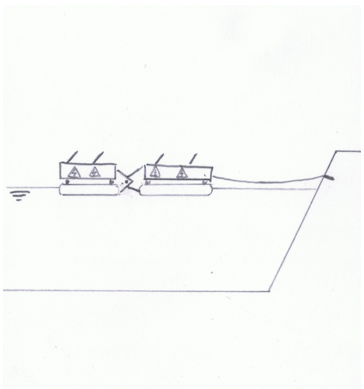
(f) Concept 6: Floating flexible bags for storage with solar panels on top and onshore PU



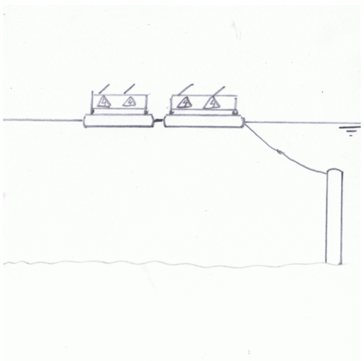
(g) Concept 7: Floating flexible bags for storage with solar panels on top and PU on bottom founded platform



(h) Concept 8: Rigid floating tanks and PU, coupled with hinges and solar panels on top



(i) Concept 9: Rigid floating tanks and PU, coupled with hinges and solar panels on top



(j) Concept 10: Rigid floating tanks and PU, flexible couplings and solar panels on top

Figure 3.1: The ten concepts developed on the basis of the morphological chart

3.2. Concept selection

The ten concepts set up in section 3.1 are evaluated in this section. The method to evaluate the concepts is based on 'The Weighted Objectives Method' described by Cross [24]. In this method, the design objectives form the criteria used to evaluate the concepts, because a good design should fulfil those objectives. The concepts are evaluated in several Multi-Criteria Analyses (MCA). First, a comparison is made between concepts with rigid floating tanks. After that, concepts with rigid or flexible tanks are evaluated. Finally, the most promising concept with floating and submerged storage are compared to each other. Sensitivity analyses are used to check the reliability of the evaluations.

3.2.1. Selection criteria

In order to assess how well the concepts score against an objective, the relative performance to the requirements that belong to that objective is estimated. For example, the objective reliable energy storage is evaluated using the requirements 'Empty reservoirs easy in motions' and 'Reliable components'. Based on the weighted average score to the requirements, grades are given to the design objectives on a scale of 0-4. A 0 means that the concept does not match the objective at all, while a 4 means an (almost) perfect match between the concept and the objective. More information on how the performance of the concepts to the requirements is determined can be found in appendix C.

The relative weights given to the objectives are determined by evaluating the relative importance of the different branches coming from one branching in the objectives tree [24]. The weight of an objective is calculated by multiplying its relative weight with the weights of the sub-objectives at higher levels. This is illustrated in fig. 3.2 where the left number under an objective represents its relative weight compared to the other objectives coming from the same branching and the right number represents the total weight of an objective. The weight going to each branch was determined by estimating the relative importance of the different branches. The reasoning why certain objectives are more important than others can be found in appendix C. This was based on the question what is most important to make this concept a success. This question has been answered for every branching separately and in consultation with a colleague. Next to that, the final weights of the leaves of the objectives tree were compared to each other, to make sure that the weights were correct relative to each other.

3.2.2. Concept evaluation

The results of the evaluation of the ten concepts are described in this section. The goal is to choose the most promising concept based on the design objectives defined in fig. 2.3. To get a reliable outcome of the evaluation, all concepts are grouped according to the kind of storage tanks used. In this way the ten concepts are divided in groups of two or three concepts, which makes it easier to reliably determine the relative performance of the concepts within one group [24]. First, the concepts were divided in two groups according to the location of the storage tanks (either submerged or floating). This resulted in one group of four concepts with submerged tanks (concepts 1 up to 4) and one group of six concepts with floating tanks (concepts 5 up to 10). These groups were again divided into two groups, one containing the concepts with rigid and one containing the concepts with flexible tanks. Thus, in total the concepts were divided into four groups, see also fig. 3.3.

To evaluate which concept is most promising, first, from each group the best concept was chosen using a MCA as described in section 3.2.1. After this, the best concept with submerged storage was chosen by comparing the best concept with submerged, rigid tanks and the best concept with submerged, flexible tanks. In the same manner the best concept with floating storage was determined.

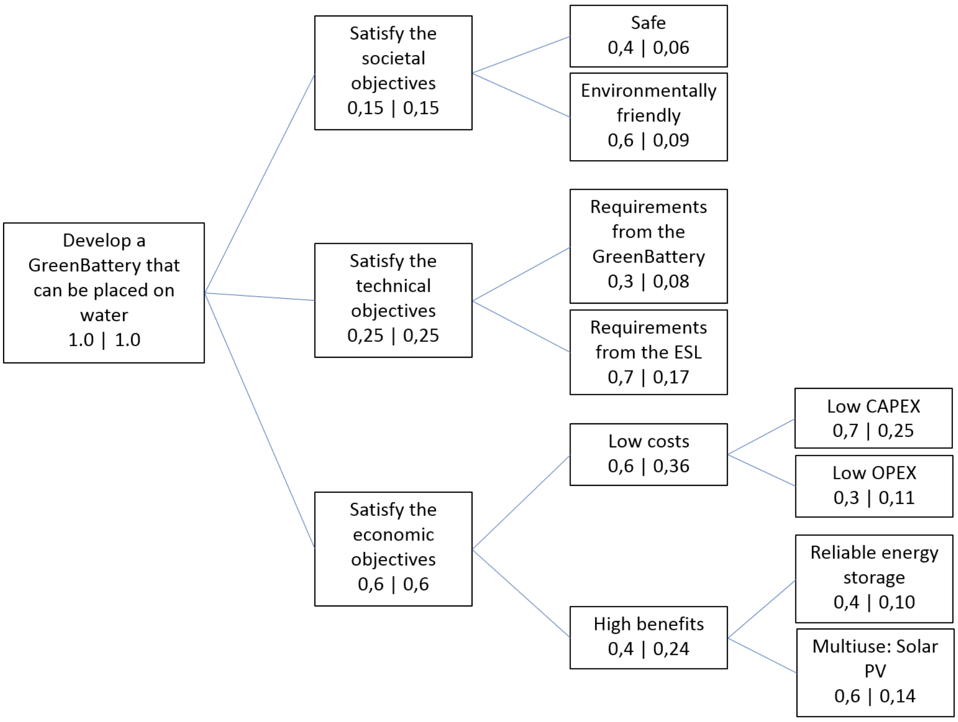


Figure 3.2: The weights given to the selection criteria using the objectives tree. The left number under an objective represents the relative weight w.r.t. the branching, while the right number is the total weight of the objective

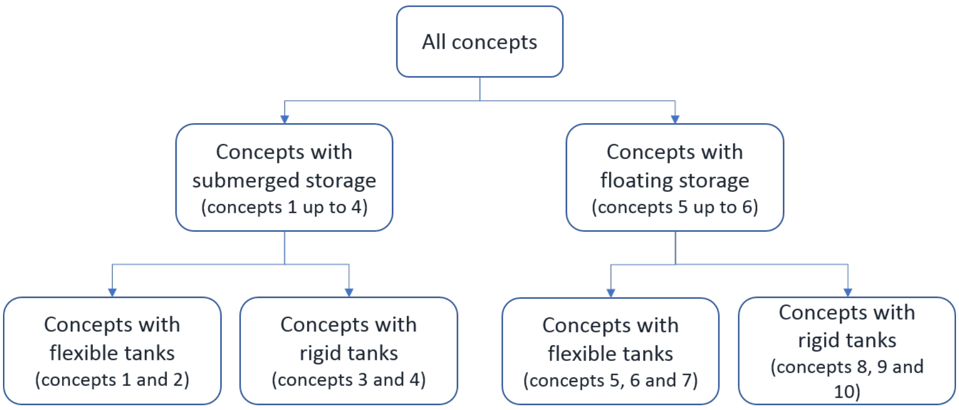


Figure 3.3: The division of the ten concepts in four groups

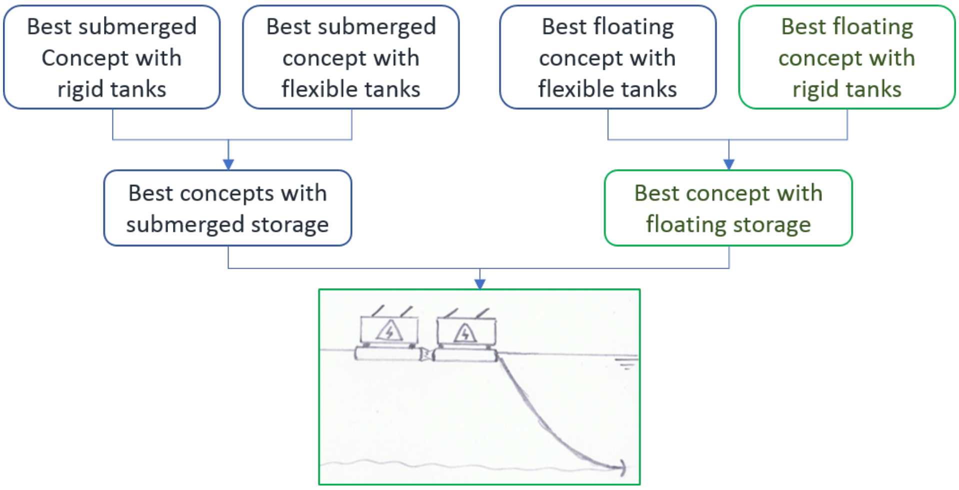


Figure 3.4: Graphical representation of the evaluation process of the concepts

Finally, the most promising concept was chosen based on the best concept with submerged and the best concept with floating storage. This is schematically presented in fig. 3.4.

Here, the evaluations in which the most promising concept appeared, the green rectangles in fig. 3.4, are described. For these evaluations, a Sensitivity Analysis (SA) was performed. The other evaluations can be found in appendix D. In this appendix, also the evaluations on requirement level are given.

The SAs are given in figs. 3.5 and 3.6. In these figures, first the influence of the scores of the concepts was investigated. This was done by randomly adding or subtracting zero or one points to the scores of the concepts. In this way 1000 different evaluations were made. This SA is expected to average the score, because the scores were not decreased further than zero or increased further than four points. Second, the influence of the weights was checked. This was done by varying the relative weights assigned to the branches in the objectives tree (see fig. 3.2). Those relative weights were varied with at maximum twenty percentage points, again in 1000 combinations. Last, the influence of both the weights and scores was determined by varying both at the same time.

3.2.3. Most feasible concept with rigid floating tanks

First, the best concept with rigid floating tanks (concept 8, 9 or 10) is chosen. The differences between these concepts are small. Only the mooring system and the connectors between the modules are different. Next to that, the choice for the mooring system is independent of the choice for the connectors. Therefore, the mooring system and the connectors are evaluated separately and no use is made of a MCA. Instead, choices are based on arguments.

The possibilities for the mooring system are: mooring lines to the lake bottom (concept 8), mooring lines to shore (concept 9) and using a pile with rope system (concept 10). The latter one has a very good ability to deal with the changes in water depth, due to the fact that the ropes can be attached to the piles at a height between the high and low water level. However, a disadvantage of this concept is that the piles will be expensive to install [2]. The option of using only mooring lines to shore is often used in floating solar PV farms, where the whole lake is covered with solar panels. However, in this case that will not be feasible, as that would mean that one large floating island of about 20 km^2 must be created that. No examples of a floating island of this size were found in literature. However, mooring lines to the lake bottom are feasible according to the companies Marine Flex (F. Bernardes, personal communication, August 11, 2020) and Seaflex (C. Gery, personal communication, August 5,

Table 3.2: MCA of concepts with flexible versus rigid tanks

Criteria	Weights	Flexible tank	Rigid tank
Solar PV	0.14	2	4
Reliable storage	0.10	1	2
OPEX	0.11	2	4
CAPEX	0.25	4	2
ESL	0.18	2	2
GreenBattery	0.08	2	3
Env. Friendly	0.09	1	4
Safe	0.06	3	2
Total:	1	2.38	2.76

2020). Furthermore, it is cheaper to realise than a mooring system with piles. Last, this mooring system consumes an equal amount of horizontal space as a mooring system with piles and ropes, because the mooring lines of different islands can overlap. Therefore, mooring lines to the lake bottom (as used in concept 8) were chosen for the mooring system.

Regarding the connectors, hinged connections (concepts 8 and 9) or flexible connections (concept 10) can be used. Hinged connections are in general more robust and can handle larger displacements, while flexible connections require less maintenance and are therefore a more attractive alternative in case of small displacements. However, at this stage the amplitude of the displacements is not known. For now hinged connections are used, as they are more robust. After a thorough hydrodynamic analysis, this choice can be reconsidered.Therefore, concept 8 is chosen as the best concept with floating, rigid tanks.

3.2.4. Concepts with rigid versus flexible tanks

In order to choose between a concept with floating rigid (concept 8), or floating flexible tanks (concept 6), a MCA was performed of which the results are given in table 3.2. The more detailed results are given in appendix D. From table 3.2, it can be seen that concepts with floating flexible tanks are expected to less expensive. According to AquaBattery, flexible tanks for use on land cost about 30 - 50 €/m^3, while rigid tanks cost about 120 - 500 €/m^3. It is expected that floating flexible tanks will be cheaper than floating rigid tanks [50]. Though, floating flexible tanks are currently only temporarily used, e.g. in case of an oil spill [15, 101]. So, the use of flexible floaters for permanent storage is not a proven technology yet. Therefore, the concept with rigid floating tanks scores better for the criteria 'Reliable storage' and 'OPEX'. Next to that, rigid floating tanks will be more environment friendly, because they can more easily be made of recyclable material, since the flexible floaters currently in use are made of layers of different materials glued together, which are difficult to separate at the end of life. Furthermore, large floating bags will contain more liquid and will be more prone to failures, resulting in a larger chance of leaking the acid or base liquids. Therefore, the concept with rigid floating tanks is chosen as the most promising floating storage concept.

A SA is done to the results of the MCA of table 3.2. The results of this analysis are given in fig. 3.5. Figures 3.5a and 3.5b give the result of the SA of the scores of the concepts to the objectives. In fig. 3.5a a box plot is given with the final scores of the concepts in the SA. Here, the edges of the box represent the 25^{th} and 75^{th} percentile. The outliers are not shown. From this figure, it can be noted that the box width is comparable, but the scores of the concept with rigid storage tanks are higher.

Table 3.3: MCA of concepts with submerged versus floating tanks

Criteria	Weights	Submerged	Floating
Solar PV	0.14	0	4
Reliable storage	0.10	4	1
OPEX	0.11	2	3
CAPEX	0.25	2	3
ESL	0.18	4	2
GreenBattery	0.08	2	2
Env. Friendly	0.09	2	3
Safe	0.06	3	3
Total:	1	2.31	2.70

Therefore, the influence of this SA on the outcome of the MCA is rather low. Figure 3.5b presents the percentage of times a concept had the highest score. It can be seen that concepts with rigid tanks score better than concepts with flexible tanks in about 80% of the cases, which confirms the conclusion that the influence of this SA on the outcome of the MCA is rather low.

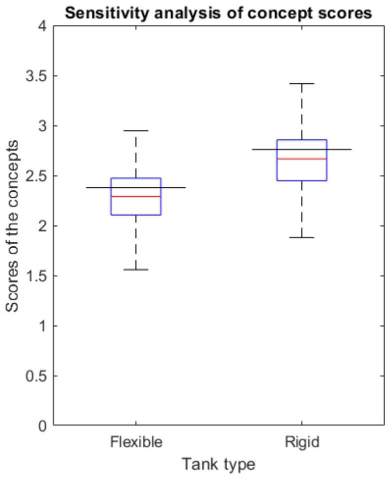
The influence of the weights is given in figs. 3.5c and 3.5d, where the box plot with the final scores of the concept is given in fig. 3.5c and the percentage of times a concept was best in fig. 3.5d. From these figures it can be concluded that the influence of the weights on the final result is minimal; the boxes in the box plot (fig. 3.5c) are relatively narrow compared to the boxes in figs. 3.5a and 3.5e. Next to that, the influence of the weights is negligible compared to the influence of the scores, because concepts with flexible tanks score better in just a few percent of the cases, see fig. 3.5d. Though, the box of rigid tanks is smaller than the box for flexible tanks. This is because rigid tanks scored high on almost all criteria, which always results in a high final score, regardless of the weights.

Figures 3.5e and 3.5f show the influence of both SAs at the same time. Because the influence of the weighs on the MCA is negligible, the results in these figures are comparable to the result of the SA where only the concept scores are varied. From fig. 3.5f it can be seen that concepts with rigid tanks score better than concepts with flexible tanks in almost 80% of the cases. Therefore, the choice for concepts with rigid floating storage tanks is valid.

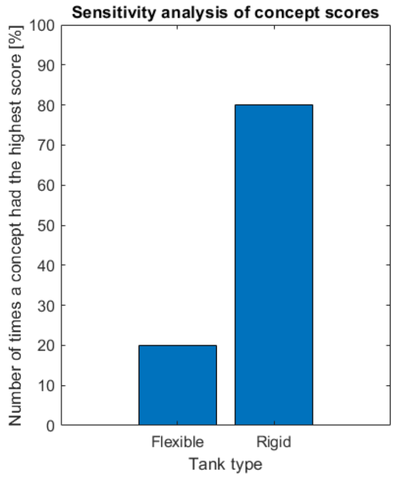
3.2.5. Concepts with submerged versus floating tanks

The results of the MCA for submerged (concept 4) versus floating (concept 8) storage concepts is given in table 3.3. From this table, it can be seen that submerged storage concepts score better on the criteria ‘Reliable storage’ and ‘Requirements from the ESL’. This is because submerged concepts are less influenced by waves and therefore it will be easier to realise a reliable submerged storage concept compared to a floating concept. However, there are enough examples of reliable floating structures, see chapter 1, so it will not be impossible to make a reliable floating structure. An advantage of a floating structure is that it can easily be combined with solar panels, thereby fulfilling the wish of Delta21. Next to that, a floating system will be easier to install and maintain than a submerged system. Therefore, the floating storage concept scores better on the criteria ‘OPEX’ and ‘CAPEX’. Therefore, the floating storage concept (concept 8) is regarded the most promising concept.

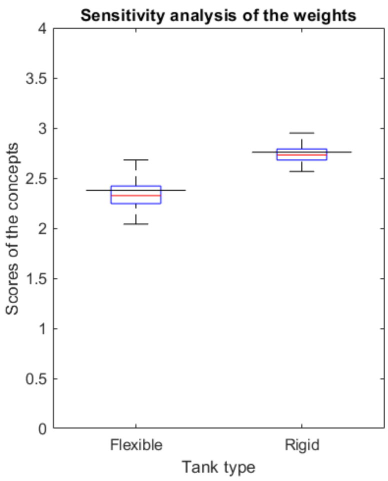
Though, because the main reason for choosing concept 8 is the possibility of multiuse with solar PV, the advantages of this combination will be further investigated in chapter 6. Furthermore, in a comparable case without the wish for the combination with solar PV, it would be interesting to investigate



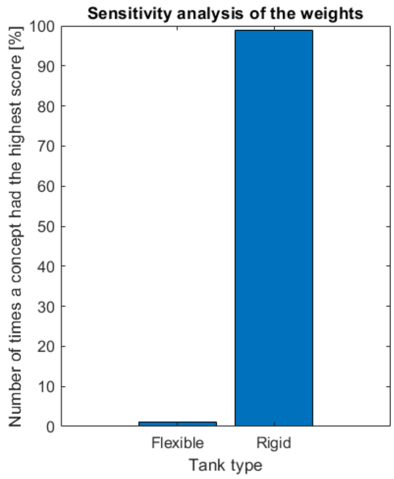
(a) Box plot presenting the influence of the scores of the concepts to the criteria on the final result. The horizontal black lines represent the result of the original evaluation



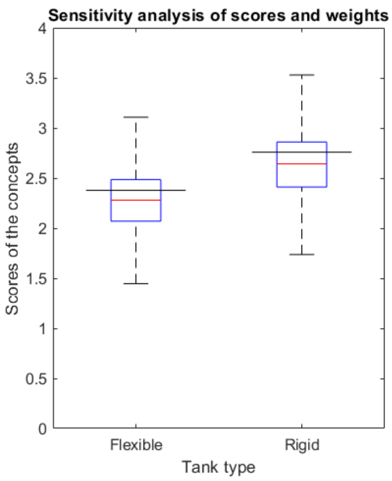
(b) Bar graph of how many times a concept was the best in the SA of the scores



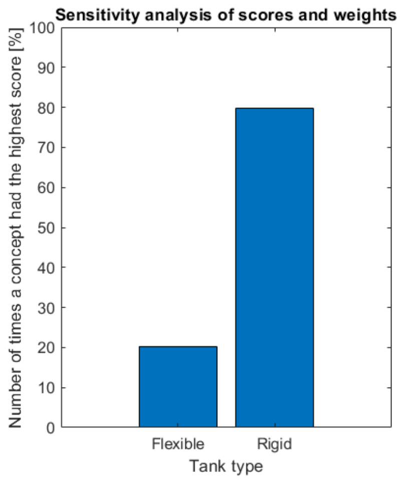
(c) Box plot presenting the influence of the weights on the final concept scores. The horizontal black lines represent the result of the original evaluation



(d) Bar graph of how many times a concept was the best in the SA of the weights



(e) Box plot presenting the influence of the weights of the criteria and the scores of the concepts to the criteria on the final result. The horizontal black lines represent the result of the original evaluation



(f) Bar graph of how many times a concept was the best in this SA

Figure 3.5: SA of the MCA for concepts with submerged or floating storage

the influence of both concepts on the efficiency, as it might be influenced by the distance over which the liquids need to be pumped in concept 4 or the distance over which the electricity must be transported in concept 8. However, this will largely depend on for instance the pipe diameter and cable thickness used in the more detailed concept design. Therefore, it is not taken into account in this evaluation. More detailed information on this MCA can be found in appendix D.

To further investigate the reliability of this evaluation, a SA is done. The results are presented in fig. 3.6. Figures 3.6a and 3.6b give the result of the SA of the concept scores. The first figure gives the variety in the final score of the concepts in a boxplot. From the second figure can be seen how often a concept had the highest score. From fig. 3.6a, it can be noted that the box widths are comparable, but the boxes have almost no overlap. Therefore, the influence of this SA on the outcome of the MCA is rather low. Figure 3.6b confirms this conclusion. It can be seen that concepts with floating storage score better than concepts with submerged storage in more than 80% of the cases.

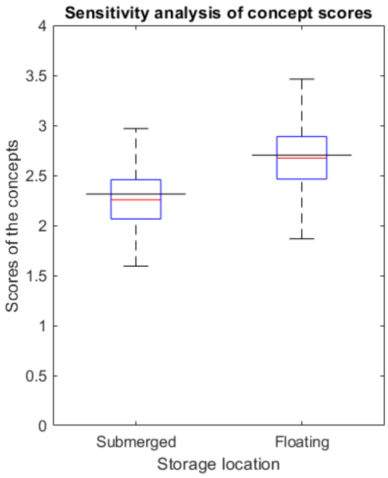
The influence of the weights is given in figs. 3.6c and 3.6d in the same manner as the influence of the concept scores. From these figures it can be concluded that the influence of the weights on the final result is rather low; the boxes in the box plot (fig. 3.6c) are relatively narrow compared to the boxes in figs. 3.6a and 3.6e. From fig. 3.6d it can be seen that the influence of the weights is smaller than the influence of the scores, because concepts with floating storage score better in more than 90% of the cases.

When both the weights and scores of the concepts are varied, a larger influence is noticed, see figs. 3.6e and 3.6f. The boxes in fig. 3.6e are again comparable in size, however the overlap is larger. This effect is also seen in fig. 3.6f, as in about 27% of the cases submerged storage concepts were best. Although this percentage is still small, it is worth checking the added value of the integration with solar PV in more detail, because the choice for floating concepts is mainly based on this argument. This is done in chapter 6.

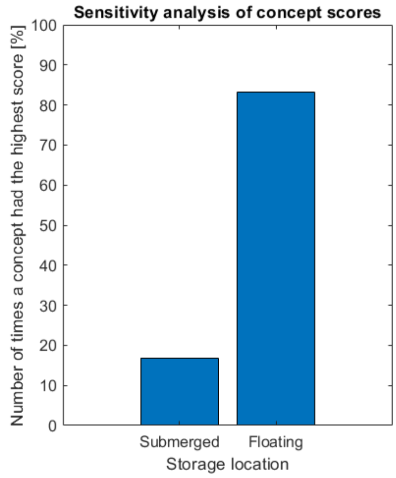
3.2.6. Conclusion

Concluding, it can be stated that the most feasible concept design for this design problem is concept 8. This is a concept with rigid floating storage tanks to store the liquids. On top of these tanks, the PU and solar panels are located. Different floating modules can be coupled together using hinged connections to form one island. Such an island can be moored using mooring lines to the seabed. This concept is schematically drawn in fig. 3.7.

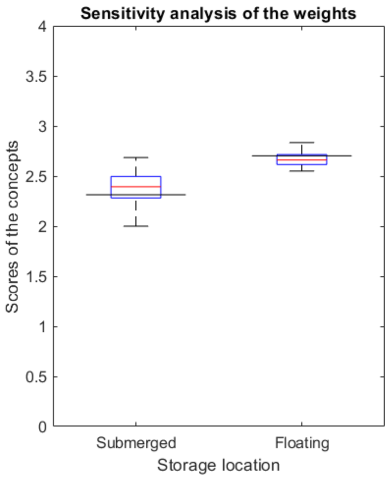
The main advantage of this concept in comparison to concepts with underwater storage is the possibility to combine this concept with solar panels. Therefore, the added value of this combination is investigated in chapter 6. Next to that, concept 8 is expected to be less expensive. A SA was performed that shows that this concept is the most feasible in more than 70% of the cases. Compared to concepts with flexible floating storage tanks, this concept is more reliable, because flexible floaters are not proven technology yet. Therefore, concept 8 is regarded most feasible.



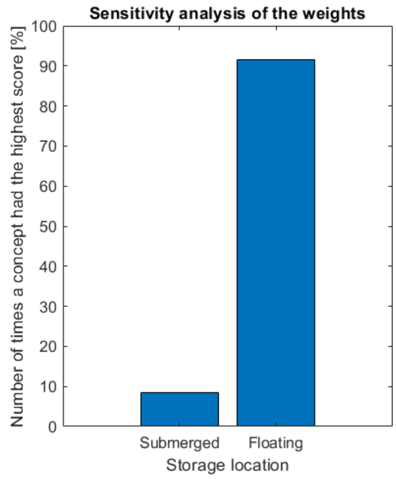
(a) Box plot presenting the influence of the scores of the concepts to the criteria on the final result. The horizontal black lines represent the result of the original evaluation



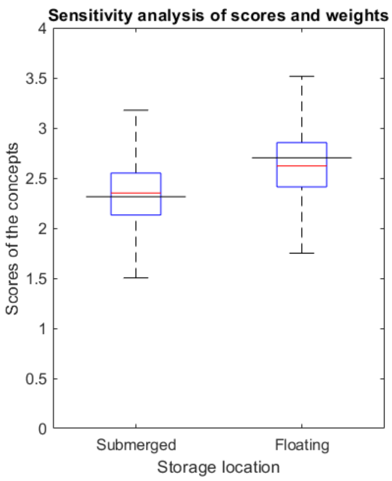
(b) Bar graph of how many times a concept was the best in the SA of fig. 3.6a



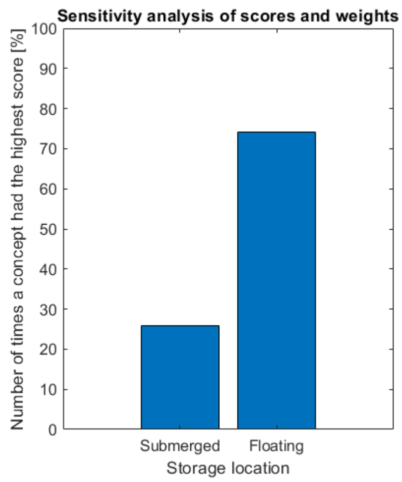
(c) Box plot presenting the influence of the weights on the final concept scores. The horizontal black lines represent the result of the original evaluation



(d) Bar graph of how many times a concept was the best in the SA of fig. 3.6c



(e) Box plot presenting the influence of the weights of the criteria and the scores of the concepts to the criteria on the final result. The horizontal black lines represent the result of the original evaluation



(f) Bar graph of how many times a concept was the best in the SA of fig. 3.6e

Figure 3.6: SA of the MCA for concepts with submerged or floating storage

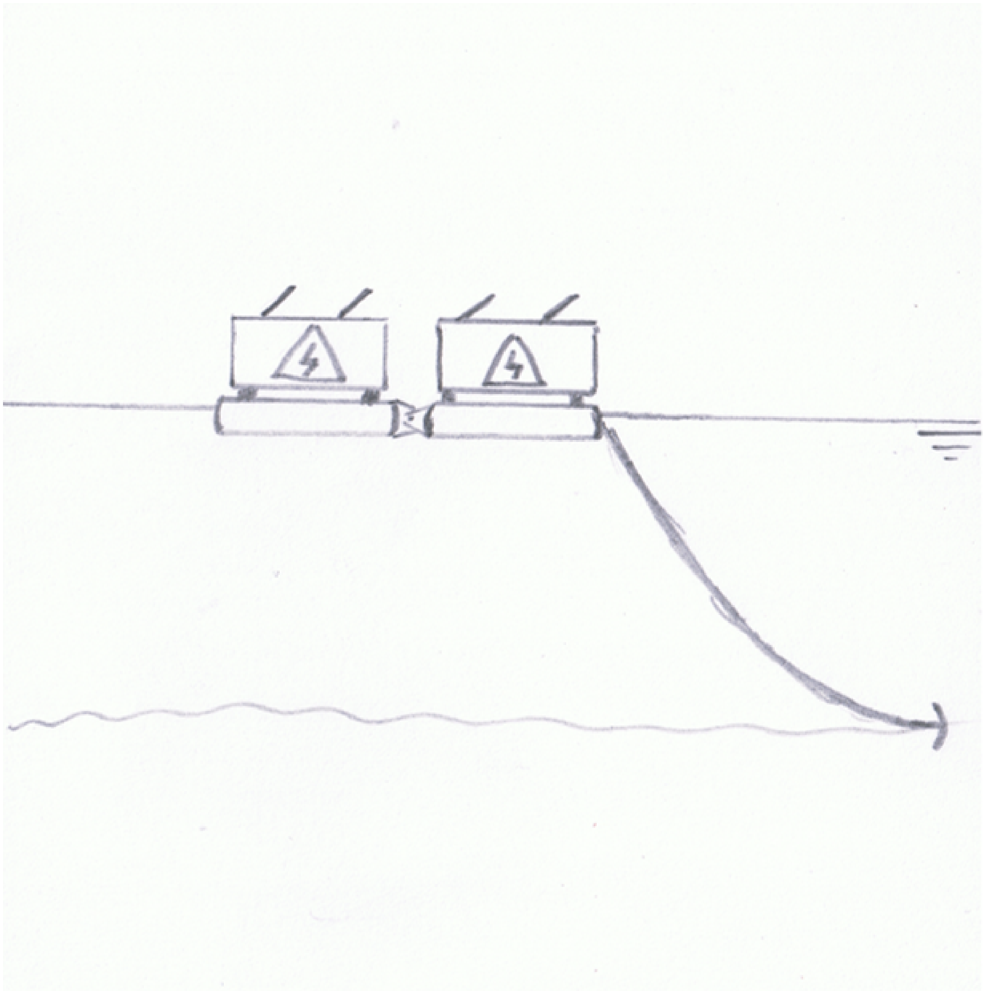


Figure 3.7: Basic sketch of concept 8

4

Concept layout

This chapter elaborates on the concept design chosen in chapter 3. To increase the modularity of the concept, the concept is build up using ‘building blocks’. Building blocks are made for the storage tanks and the PU. These are combined to form one module. Different modules are combined to form one floating island. Finally, the ESL can be filled with the floating islands.

Of course, for every level of building blocks different options are possible. To determine the most feasible option, a set of requirements is generated. These requirements are described in the first section. The second section describes the building blocks used to make the concept.

4.1. Requirements for the concept layout

The requirements for the layout of the concept are generated by brainstorming and in consultation with colleagues. The final set of requirements is given in table 4.1. In the left column of this table, the requirements are given. The middle column denotes whether the requirement is a demand or a wish. A short explanation on the requirements and why it is important is given in the right column.

4.2. Building blocks

This section describes the different building blocks. The different options are evaluated using the requirements in table 4.1. Using these requirements, the ad- and disadvantages of the different options for the building blocks are listed. On the basis of these arguments, a choice is made for one of the options.

4.2.1. Storage tanks

For the tanks, two possible building blocks exist. First, all tanks can be placed in one floater. In this case, one floater would be divided into several compartments, each being a tank. The second option is to make one floater for each tank. Here, multiple floating tanks would form one module together and liquid transport between the floaters would be required. The ad- and disadvantages of both building blocks can be found in table 4.2.

From the arguments listed in this table, the conclusion is drawn that the best option is to house all tanks in one floater. In this way, no extra space needs to be reserved for buoyancy, thereby increasing

Table 4.1: The requirements for the layout of the chosen concept in the ESL

Requirement	**W/D**	**Explanation**
Scalable volume of tanks vs PU	Demand	Tank volume must be 7-70 times larger than PU, due to scalability of the storage duration and the difference in power (5 kW/m^3) and energy density (10 kWh/m^3).
Scalable coverage of ESL	Wish	To adjust the capacity of the system to the wishes of the final client
Easy maintenance access	Wish	To minimise the maintenance costs
Possibility to maintain PU on land	Wish	It is safer to maintain the PU on land, because it can be labour intensive
Easy installation	Wish	To minimise installation costs
Easy transportability of components	Wish	All components should fit on a lorry to ease the transportation
4 tank types	Demand	Salt water, acid, base and demineralised water tanks are needed. Note, the demineralised water tank is relatively small and is therefore assumed to be placed inside the PU.
Liquid volume ratio: 1:1:2 for volume of acid:base:saltwater	Demand	Prescribed by the GreenBattery.
Tank volume ratio: 1:1:4 for volume of acid:base:saltwater	Demand	It must be possible to pump all liquids in the salt tanks. Therefore, the salt tank must be twice as large as the volume of salt water.
Possibility to completely drain the acid and base tanks	Demand	To 'reset' the system, all liquids must be pumped into the saltwater tank
Maximize storage capacity	Wish	With a larger storage capacity, a smaller part of the lake needs to be filled to serve the clients wishes.
Double walled tanks for storing the acid	Demand	According to the ADN regulations, see table 2.4.

Table 4.2: Different building blocks for the tanks with the ad- and disadvantages

Tank type	Advantages	Disadvantages
Separate floater for each tank	Largest volume per tank	Sometimes empty floaters, which would induce larger forces on the module connectors
	Simplest tanks	Liquid transport between different floaters needed
		Tanks can not be filled to the maximum, because buoyancy is needed
One floater, separate compartments	Extra volume in saltwater tanks creates extra buoyancy	More complex tank
	Automatic partially double walled tanks for the acid and base	

Table 4.3: Possible configurations of tank and PU within one module with the ad- and disadvantages

Type:	Advantages:	Disadvantages:
PU on top of the tanks	Good maintenance access to all components	Possibility of shadow on PV panels
PU under the tanks		Difficult to reach the PU for maintenance
PU next to the tanks	Good maintenance access to all components	Extra horizontal space needed for the PU

the storage capacity of one floater. Next to that, the tanks for the acid and base can be placed in the middle, thereby minimising the need for double walled tanks.

4.2.2. Power unit

The PU itself is already modular. Multiple membrane stacks can be coupled in series or parallel to generate the required power. In the current pilot system of the GreenBattery four membrane stacks are used to generate 1 kW together.

For the building blocks of the PU two options are available in this case. First, the PU can be integrated in a separate floating structure. Second, a container with the PU can be made that can be placed on top of a floating structure. However, which option is most suitable for this case, depends on the module configuration.

4.2.3. Module configuration

The tanks and PU can be combined into one module in three different manners. The PU can be placed on top of, under or next to the tanks. The ad- and disadvantages of these three configurations can be found in table 4.3.

The two requirements that influence this choice are ‘Easy maintenance access’ and ‘Maximize storage capacity’. The maintenance access is best for the configurations with the PU next to or on top of the tanks. However, when the PU is placed next to the tanks, extra horizontal space is used. In case

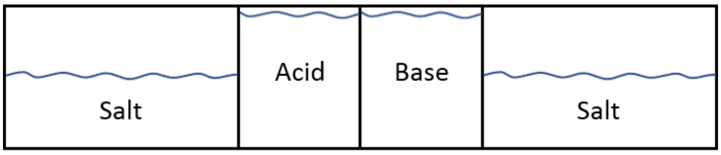


Figure 4.1: Schematic side view of one floating container. The reservoirs for the salt water are twice as long as the reservoirs for the acid or base

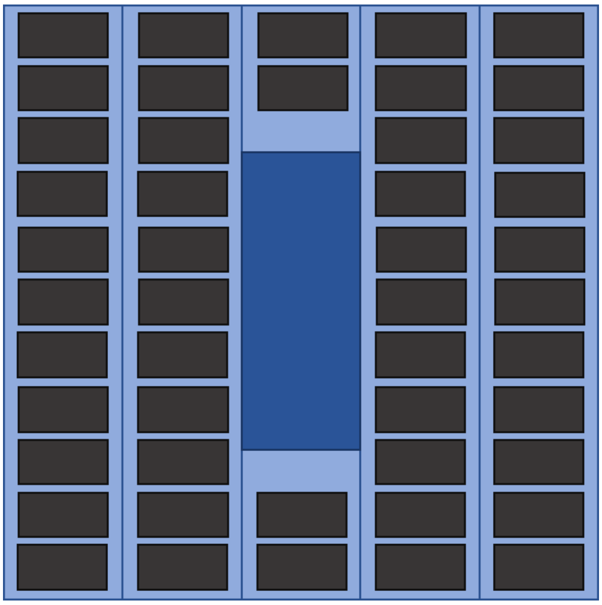


Figure 4.2: Schematic top view of one module. The light blue, black and dark blue rectangles represent the floating containers, solar panels and PU respectively

the PU is placed on top of the tanks, the buoyancy that is present in the tanks can be used to keep the PU afloat. Therefore, the configuration with the PU on top of the tanks is chosen.

Resulting module configuration

One module consists of five floating container-like tanks with the size of a 40 ft container for easy transportability. In this way, a module of about 12 by 12 meters is created. For more information about such a floating container, see [14]. Please note, this container is made to form a large floating pontoon, not to carry liquids. However, the idea can be used in making the floating tanks. All containers contain an acid, a base and a salt water tank. In this way, the containers contain a constant liquid volume, minimizing the forces on the couplings between the tanks. Next to that, during the hydrodynamic analysis in chapter 5 it was noted that one tank per container would lead to instability. Therefore, multiple tanks per container are necessary. The tanks in different containers can be interconnected to make sure that the concentration in the tanks of the same kind is the same. However, when this is implemented in the final design, the influence of this decision on the hydrostatic stability should be investigated.

A schematic overview of one tank is given in fig. 4.1 for a typical filling condition. The acid and base tanks are placed in the middle, so that the salt water tanks form part of the double walls. On top of these tanks, the PU and solar panels are placed. The PU is placed inside a container. This container should be made replaceable, so that the container can be shipped to shore and maintenance can take place onshore. A schematic top view of one module is presented in fig. 4.2.

One module with contains in total about 100 m^3 of salt water, 50 m^3 of acid and 50 m^3 of base

Table 4.4: Possible configurations of one floating island with the ad- and disadvantages

Type:	Advantages:	Disadvantages:
One large island	Maximum storage capacity	Difficult to reach all modules for maintenance Large mooring forces Never done before on this scale Not scalable
Separate modules	Good accessibility for maintenance and installation	Every module needs to be moored (more difficult and costly installation) Low storage capacity
Circular islands		Difficult to reach middle modules for maintenance/ maintain PU on land
Rectangular islands	Every module accessible for maintenance	

water, in accordance with the requirements. The energy density of the GreenBattery is expected to be about 10 kWh/m^3 of liquid volume, by the time the ESL should be finished. This gives a total storage capacity of about 2 MWh per module. With a storage duration of 100 h, this means that the PU should have a power capacity of about 20 kW. In total there is space for about 48 solar panels of 1 by 2 m on one module. With a peak power output of 300 W$_p$ per panel [37], this gives total peak power of 14.4 kW$_p$.

For a module with a storage duration of 10 h, it is not possible to completely fill the tanks, because the size of the PU needs to increase. This results in extra weight, which resulted in a draft almost equal to the height of one container. Therefore, it was chosen to fill the tanks for only 80%. This results in a storage capacity of 1.6 MWh per module and a power capacity of 160 kW. With a power density of about 5 kW/m^3, the PU fits in a regular 20 ft container for all storage duration between 10 and 100 h.

4.2.4. Configuration of one floating island

Multiple of these modules can be coupled together to form one floating island. Different shapes of floating islands are possible. One large floating island covering the whole surface of the lake can be created, but all modules can also be moored separately. Furthermore, the lake can be filled with circular or rectangular floating islands. These options are compared to each other in table 4.4, where the ad- and disadvantages of each option are listed.

One large island is not regarded feasible because of its size; the island would need to be about 20 km^2 large, which is never done before. Next to that, with such a large floating island, it is difficult to reach modules in the middle for maintenance. For this same reason, circular islands are impractical in use. Rectangular islands with a maximum of two rows of modules next to each other do not have this problem, because every module can be reached over water. This is useful when heavy components need to be replaced. Of course carrying out maintenance would be easiest when every module is moored separately, however this would decrease the storage capacity of the lake significantly. Therefore, the use of rectangular islands consisting of two rows of modules is chosen.

In fig. 4.3 a schematic top view of one floating island is depicted. The length of the floating island is chosen to be eight modules. This gives a total length of about 100 m, which is comparable to the length of an average inland ship. In this way, 16 modules are coupled together to form one rectangular

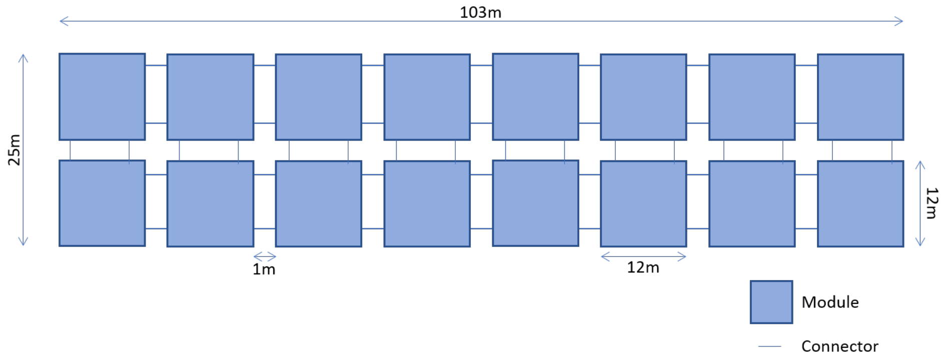


Figure 4.3: Schematic top view of one floating island. The blue squares represent the modules and the lines in between the modules represent the module connectors

Table 4.5: Energy and power capacity of one floating island

Quantity	Magnitude
Storage capacity battery	26 - 32 MWh
Power capacity battery	320 kW - 2.6 MW
Power capacity solar PV	230 kW$_p$

island. The total energy and power capacities of one floating island are given in table 4.5. Note that the power of the battery is scalable to the wishes of the client.

A preliminary design of the mooring system for this floating island is kindly provided by the company Marine Flex and shown in fig. 4.4. An elastic (taut) mooring system is chosen, because of its good ability to deal with changing water depths. For a Catenary mooring system, normally the horizontal distance needed for the mooring lines is about three times the maximum water depth, while the elastic mooring system of Marine Flex only needs about one time the maximum water depth for horizontal distance, according to conversations with Marine Flex. Next to that, the elastic mooring lines do not lie on the ground, and thereby do not disturb the flora and fauna on the bottom of the lake. Note that the horizontal space needed for the mooring system is larger than one times the water depth. However, Marine Flex noted that this horizontal space could be decreased if necessary.

4.2.5. Layout in ESL

The surface of the ESL can be filled with the floating islands described above. To calculate the maximum capacity of the lake, the usable surface area of the ESL needs to be known, as well as the horizontal surface needed for one floating island. The surface of the ESL at low water is about 22.9 km^2, see chapter 2. Though, the islands are not allowed to be placed in close proximity to the pumps and syphons, a distance of about 500 m should be kept. This means that in total about 20 km^2 of the lake can be filled with the floating islands, since the pumps and syphons are both about 2 km long.

The outer dimensions of one floating island is about 25 by 103 m, as can be seen in fig. 4.3. The horizontal distance between two floating islands is assumed to be about 50 m, as Marine Flex noted that the horizontal distance needed for anchoring could be decreased and the anchor lines could be partially overlapping. This means that for one floating island in total about 11500 m^2 is needed. In this way, in total about 1500 floating islands can be placed on the ESL. The total capacity of these islands together is given in table 4.6.

From fig. 1.2 it can be seen that the required storage capacity by 2030 is expected to be about 16

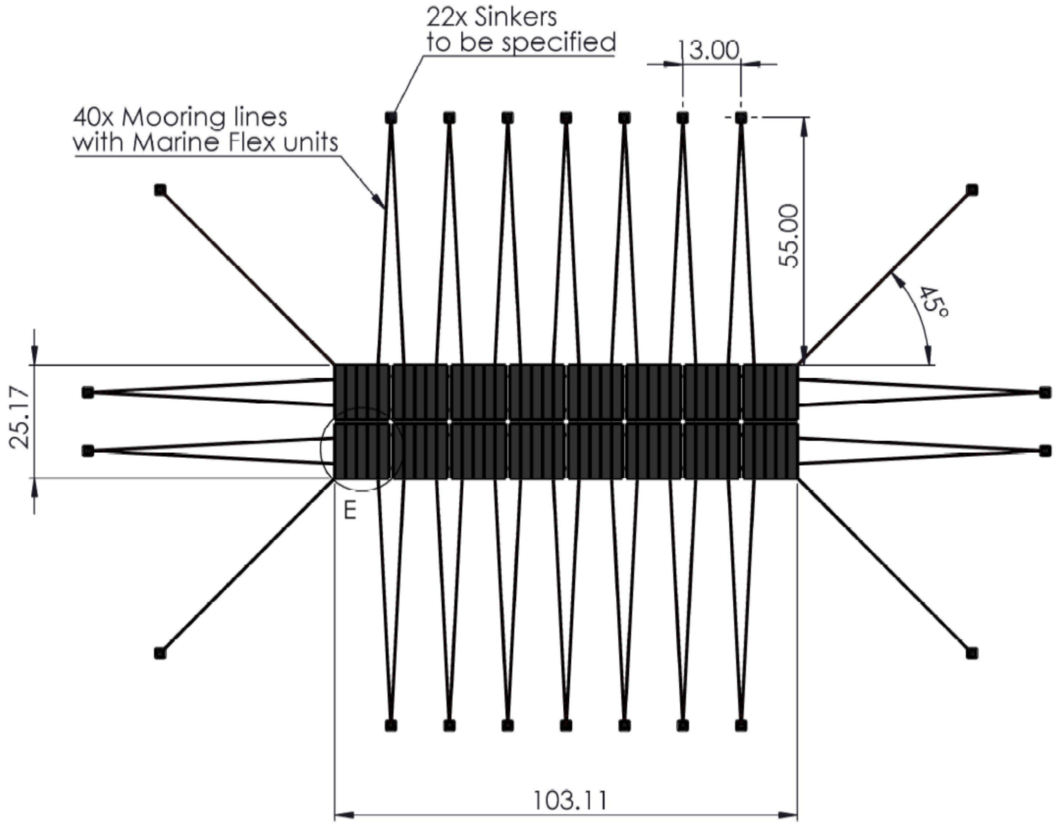


Figure 4.4: Top view of the mooring layout provided by Marine Flex

Table 4.6: Energy and power capacity of the complete system consisting of 1500 floating islands

Quantity	Magnitude
Storage capacity battery	38 - 48 GWh
Power capacity battery	480 MW - 3.8 GW
Power capacity solar PV	345 MW_p

GWh for a storage duration of 10 h. For a storage duration of 100 h, a capacity of about 130 GWh is required. The maximum storage capacity of the lake is 48 GWh, see table 4.6. Therefore, when a storage duration of 10 h is chosen, it will not be required to fill the whole lake. The concept can easily be adjusted to the wishes of the client, by varying the amount of islands.

From fig. 4.4 it can be seen that about 40 mooring lines are needed per island. If the whole lake is filled with floating island, this means that in total about 60,000 mooring lines are needed. Installing these would be a large operation. Therefore, in a next design iteration, the number of mooring lines per island should be reduced.

The floating island should be connected with floating electricity cables to one converter island in the middle of the lake. From this point, one floating electricity cable can be made to the existing grid. The electricity cables should be floating, as this is cheaper than submerged cables [2].

4.3. Weight and inertia estimation

The calculated weight and moment of inertia around the x, y and z axis, see fig. 4.5, of the components of one module for a storage duration of 10 and 100h can be found in tables 4.7 and 4.8 respectively. The masses are calculated by multiplying the unit weight with the amount of units needed for one module. The moments of inertia are estimated using the geometry of basic rectangles. For the tanks, the PU and solar panels, the following equation is used:

$$I = \frac{1}{12} m \left(H^2 + L^2\right) \tag{4.1}$$

In which I is the moment of inertia of the component, m the mass of the component and H and L are the main dimensions of the rectangle perpendicular to the axis of rotation. The moments of inertia of the different components are transferred to the Centre of Gravity (COG) of the module using Steiner's formula:

$$I_{COG} = I + mr^2 \tag{4.2}$$

Where r is the shortest distance from the COG of the component to the axis of rotation through the COG of the module. In this analysis, the weight of the mooring system is assumed to be negligible. The moment of inertia of the module connectors itself is assumed to be negligible as well, but the Steiner term is taken into account.

The mass moment of inertia of the liquids in the tanks is estimated using the analytical equation proposed by Lee [67]. Note, this equation is valid for fully filled tanks, but in this case also used for estimating the mass moment of inertia for tanks that are not fully filled. For a rectangular tank with length L and height H, this equation becomes:

$$I = I_{solid} - m_{liquid} \sqrt{\frac{\pi}{4}} \frac{L^2 H^2}{\pi \left(H^2 + L^2\right)} \tag{4.3}$$

With $I_{solid} = \frac{1}{12} m_{liquid} \left(H^2 + L^2\right)$ and m_{liquid} the mass of the liquid stored in the tank.

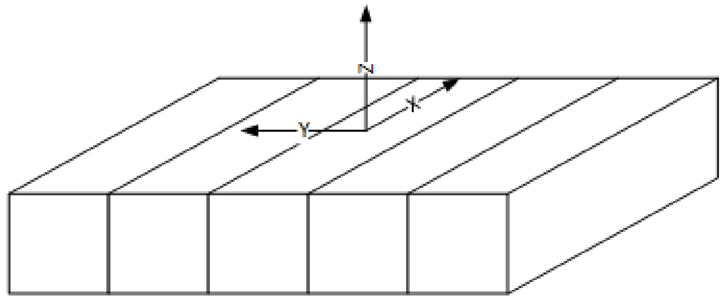


Figure 4.5: Coordinate system for one module of 12.2 by 12.2 by 2.44 m

Table 4.7: Weight estimation in metric tonnes for one module with a storage duration of 10 h, with KG the height of the COG w.r.t. the keel and the moment of inertia w.r.t. the COG

Component	Weight per unit	Amount	Weight [t]	KG [m]	I_x [tm^2]	I_y [tm^2]	I_z [tm^2]	Source
Tanks	11.5 [t/tank]	5	57.5	1.22	751	751	1426	[14]
Salt water	1.04 [t/m^3]	80	83.2	0.46	1077	1518	2406	
Acid + base	1.00 [t/m^3]	80	80	0.92	963	130	1083	
PU	0.5 [t/kW]	160	80	3.44	531	318	267	
Solar panels	0.04 [t/piece]	48	1.9	2.64	25	25	46	[37, 45, 92]
Connectors	0.1 [t/piece]	6	0.6	2.20	23	23	29	
Total:			303	1.62	3394	2788	5257	

Table 4.8: Weight estimation in metric tonnes for one module with a storage duration of 100 h, with KG the height of the COG w.r.t. the keel and the moment of inertia w.r.t. the COG

Component	Weight per unit	Amount	Total weight [t]	KG [m]	I_x [tm^2]	I_y [tm^2]	I_z [tm^2]	Source
Tanks	11.5 [t/tank]	5	57.5	1.22	745	888	1426	[14]
Salt water	1.04 [t/m^3]	100	104	0.58	1251	1801	3008	
Acid + base	1 [t/m^3]	100	100	1.15	1167	126	1353	
PU	0.5 [t/kW]	20	10	3.44	91	64	33	
Solar panels	0.04 [t/piece]	48	1.9	2.64	28	28	46	[37, 45, 92]
Connectors	0.1 [t/piece]	6	0.6	2.20	23	23	29	
Total:			274	1.04	3303	2786	5896	

5

Technical feasibility

In this chapter, the technical feasibility of the concept described in chapter 4 is estimated. First, it is determined which phenomenon would cause the most important response. After that, it is estimated whether this response will be present in the current concept. Finally, the dimensions of this concept are varied to minimise the most important response and new dimensions are proposed.

5.1. Most important response

In most systems, the most destructive, and thus important, response happens when the system is excited at one of the natural frequencies of the system. This is made visible in fig. 5.1, where the response amplitude is drawn for a linear mass-spring-damper system with different exciting frequencies and different values of the damping. For floating systems, the damping ratio, δ in fig. 5.1, is far below one, which means that the response with the highest amplitude occurs around the natural frequency [34]. The amplitude is than dominated by the damping [56].

In this case, the repetitive loads are mainly induced by the waves, winds and currents [42]. To see which phenomenon is most likely to cause cyclic loads with a period close to the natural period of the floating island, the excitation periods of these phenomena are estimated and compared to the natural periods of the floating system.

The peak period of the wave forces is estimated to be 2.7 - 4.2 s, for a fetch of 1 or 5 km respectively. When the lake is filled with the floating islands, a maximum fetch of about 1 km is observed between the shore and the first floating island, see also fig. 2.1. According to Peña et al. [79], a floating breakwater with a width of 12 m and a draft of 1.8 m is able to half the wave height for periods up to 3.6 – 4.1 s. Therefore, it is assumed that the waves will not be able to build up to larger heights than when they reach the first modules. Therefore, the largest wave period that will be present in the lake is expected to be around 3.0 s when the lake is filled with floating islands and about 6.5 s when only one floating island is placed in the lake, because the JONSWAP spectra presented in fig. 5.2 are about zero for these wave periods. A JONSWAP spectrum is used, because this gives an accurate prediction of the wave spectrum for young sea states [51].

The wind load is mainly related to the wind speed. The wind speed can be represented by a Van der Hoven spectrum according to Arany et al. [7] and Escalante Soberanis and Mérida [39]. According

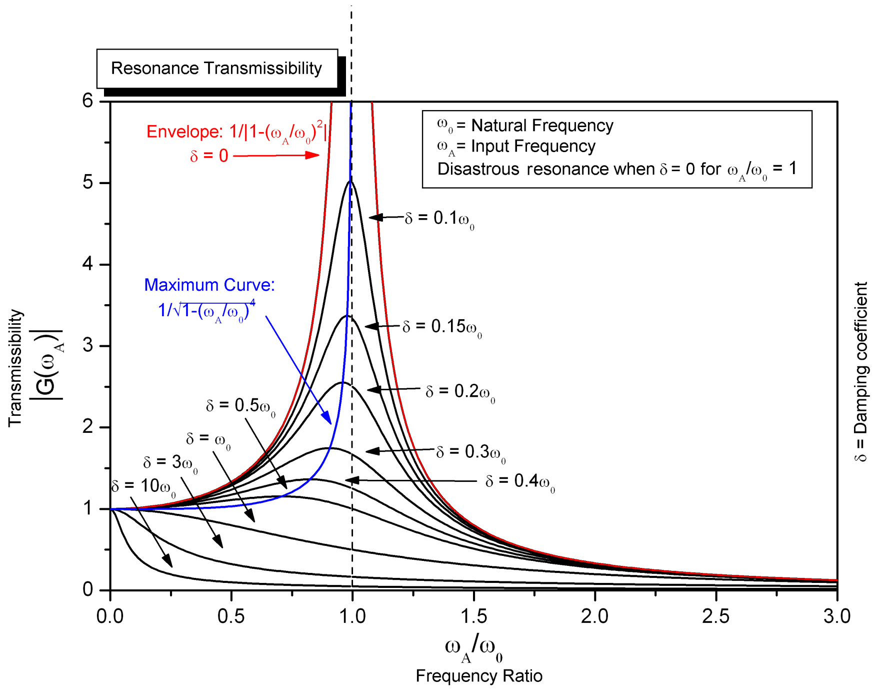


Figure 5.1: The largest response occurs when the exciting frequency equals the natural frequency. Figure copied from [71]

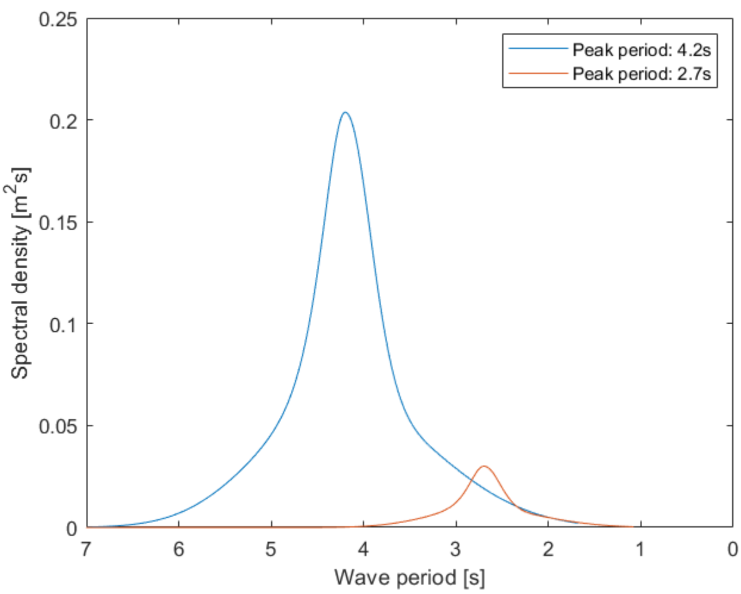


Figure 5.2: The JONSWAP wave spectrum for a peak period of 4.2s and 2.7s

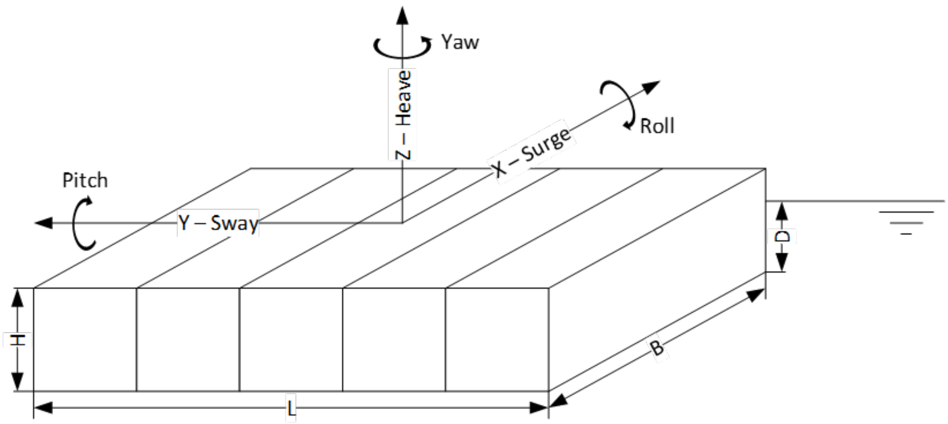


Figure 5.3: Definition of the six DoFs of one floating module and the dimensions

to this spectrum, the wind speed has peak values for periods of about four days, two days and one minute.

The currents in the ESL are induced by the pumps. Since this lake will be used for day-night energy storage, the period of the currents is expected to be about 24 h.

The natural periods of the floating island should not be close to one of the exciting frequencies, to prevent large forces and motions. Therefore the natural periods of the proposed concept are calculated in this chapter and a design iteration is made.

5.2. Method to calculate the natural periods of the floating island

A rigid body normally can move in six Degrees of Freedom (DoFs), unless the body is restricted. Those DoFs and their corresponding names can be found in fig. 5.3. In this figure, one floating module is depicted with its DoFs.

A floating system is often modelled as a first order mass-damper-spring system [16]. Water induces hydrostatic stiffness, linear damping and an added mass term. Therefore, the Equations of Motion (EoM) becomes:

$$(M + A)\ddot{x} + B\dot{x} + Kx = f \tag{5.1}$$

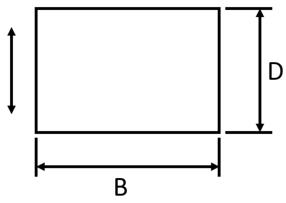
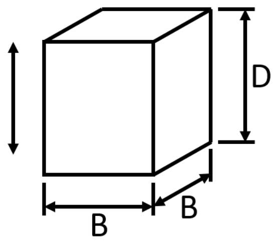
In which matrices M, A, B and K contain the mass, added mass, damping and hydrodynamic stiffness respectively. The dimension of these matrices is $6N$ by $6N$, with N the number of floating bodies, with six DoFs per floating body. x is a vector containing the displacements in every DoF. $\dot{x}$ and $\ddot{x}$ are vectors containing the first and second derivative with respect to time of the displacement vector x respectively. Vector f is a force vector containing the wave excitation forces. The vectors in eq. (5.1) have dimensions of $6N$ by 1.

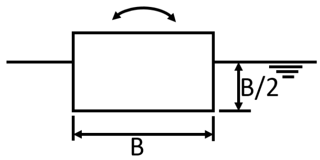
The natural frequencies (ω) of this system can be calculated using the eigenvalues of the EoM [34] as shown in eq. (5.2). In hydrodynamics, often a distinction is made between the wet and dry natural frequencies. The wet natural frequency is calculated including the added mass matrix, while the dry natural frequency is calculated excluding the added mass.

$$\det\left(-\omega^2(M + A) + K\right) = 0 \tag{5.2}$$

The natural periods T can then be calculated using:

Table 5.1: Added mass data for a fully submerged structure provided by DNV-GL [100]

Setup 2D	B/D	C_a	Setup 3D	D/B	C_a
	∞	1		1	0.68
	10	1.14		2	0.36
	5	1.21		3	0.24
	2	1.36		4	0.19
	1	1.51		5	0.15
	0.5	1.7		6	0.13
$a_{heave} = 0.25 C_a \rho \pi B^2 L$	0.2	1.98	$a_{heave} = C_a \rho B^2 D$	7	0.11
	0.1	2.23		10	0.08



$$a_{pitch} = 0.117 \rho \pi (B/2)^4 L$$

Figure 5.4: Added mass moment of inertia data for a floating structure according to Wendel [108]

$$T = \frac{2\pi}{\omega} \tag{5.3}$$

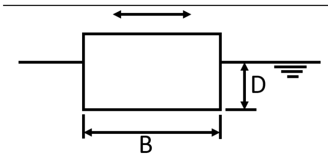
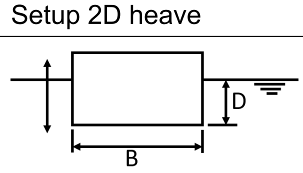
Also the mooring system has a stiffness, and will therefore result in a natural period in surge, sway and yaw direction. However, the mooring stiffness is often a higher order function and is therefore not taken into account in the first order EoM. Next to that, the natural periods of a mooring system are normally much larger than the natural periods of the floating system itself and are therefore not the most critical response [56]. However, when this concept is further elaborated, a more detailed analysis on the natural periods of the mooring system should be carried out.

5.2.1. Calculation of the added mass

The added mass and added mass moment of inertia of one module is estimated using analytical equations described by DNV-GL [100] (see table 5.1), Clauss et al. [20] (see table 5.2) and Wendel [108] (see fig. 5.4). The data of table 5.2 was originally given for different wave periods. Here, the data is given that is valid for a wave period of 2.7 s in combination with the dimensions of one module as presented in chapter 4. The added masses in surge, sway and heave direction are calculated according to the equations described by Clauss et al. [20], while the added moments of inertia in roll and pitch direction are calculated using the equations described by Wendel [108]. Wendel also noted that the added moment of inertia for a plate is 93.6% of the added moment of inertia according to fig. 5.4.

To account for the correct breadth over draft ratio (B/D) the data was interpolated between the given points. The B/D is in this case 6.8. The difference between the added mass for a 2D or 3D system is shown by DNV-GL [100]. This data is extrapolated using a spline function to estimate the difference in added mass between 2D and 3D for B/D = 6.8. The result is that the added mass for a 3D system is about 60% of the added mass of a 2D system.

Table 5.2: Added mass data for a floating structure provided by Clauss et al. [20]

Setup 2D surge	B/D	C_a	Setup 2D heave	B/D	C_a
	2	0.074		2	0.71
	4	0.032		4	0.59
	8	0.153		8	0.50
$a_{surge} = C_a \rho \pi D^2 L$			$a_{heave} = 0.25 C_a \rho \pi B^2 L$		

5.2.2. calculation of the hydrostatic stiffness

The stiffness of the module in heave, roll and pitch direction is calculated according to the equations described by [56]. For heave direction, the stiffness (K_{Heave}) can be calculated with:

$$K_{Heave} = \rho_w g A_{wl} \tag{5.4}$$

In which ρ_w is the density of water, g is the gravitational acceleration and A_{wl} is the water line area (BL in this case). For roll direction, the stiffness (K_{Roll}) is calculated with:

$$K_{Roll} = \rho_w g \nabla GM_{Roll} \tag{5.5}$$

In which ∇ is the underwater volume of the module and GM_{Roll} the metacentric height. The stiffness in pitch direction (K_{Pitch}) can be calculated in the same manner as K_{Roll}, but using GM_{Pitch} instead of GM_{Roll}. The metacentric height is calculated using:

$$GM = KB + BM – KG – GG' \tag{5.6}$$

In which KB is the distance between the keel and Centre Of Buoyancy (COB), in this case half the draft. BM is the distance between the COB and the metacentre, which can be calculated according to eq. (5.7). KG is the distance between the keel and the COG and GG' is the reduction in metacentric height due to the presence of tanks with a free surface. The equation to calculate the GG' is presented in eq. (5.8).

$$BM = \frac{I_t}{\nabla} \tag{5.7}$$

Where I_t is the surface moment of inertia of the waterline area, in this case $I_t = \frac{1}{12} BL^3$ with L and B the length and width of one module.

$$GG' = \frac{\sum \{\rho_f i_t\}}{\rho_w \nabla} \tag{5.8}$$

With ρ_f the density of the fluids stored in the tanks and i_t the surface moment of inertia of the free surface in the tanks.

5.2.3. Natural periods of a system with one floater

For one module, eq. (5.2) can be simplified into six separate equations, one for every DoF, because the off-diagonal terms in the added mass matrix are zero due to the double symmetry in one module. Leaving out the damping matrix, which is not needed for the calculation of the natural periods, a system of six uncoupled equations is created. Because the hydrostatic stiffness is only present in heave, roll and pitch direction, only the equations related to these motions have a natural period. The equations to calculate the natural periods become:

$$T_{Heave} = 2\pi \sqrt{\frac{m + a_{Heave}}{K_{Heave}}} \tag{5.9}$$

$$T_{Roll} = 2\pi \sqrt{\frac{I_x + a_{Roll}}{K_{Roll}}} \tag{5.10}$$

$$T_{Pitch} = 2\pi \sqrt{\frac{I_y + a_{Pitch}}{K_{Pitch}}} \tag{5.11}$$

With T_{Heave}, T_{Roll} and T_{Pitch} the natural periods for heave, roll and pitch motion respectively, m the mass of one module, I_x and I_y the mass moment of inertia in x- and y-direction of one module and a_{Heave}, a_{Roll} and a_{Pitch} the added mass and added mass moments of inertia for the heave, roll and pitch motions.

5.2.4. Natural period of a system with multiple floaters

Equation (5.1) is also valid for floating systems consisting of multiple floaters. But, to make it suitable for the concept presented in chapter 4, an extra stiffness matrix must be introduced to account for the couplings between the floaters [111]. The EoM becomes:

$$(M + A)\ddot{x} + B\dot{x} + (K + C)x = f \tag{5.12}$$

Where C is the extra stiffness matrix that accounts for the couplings. The equation to determine the natural frequencies becomes:

$$\mathbf{det}\left(-\omega^2(M + A) + (K + C)\right) = 0 \tag{5.13}$$

The natural periods can then be calculated using eq. (5.3).

Added mass for a multibody system

For investigating the natural periods of a floating island consisting of multiple modules, hydrodynamic data of a 2D floating island, that was obtained during the course Fluid Structure Interaction in Marine Structures (MT44090), was used. This floating island consisted of 12 rectangular modules of 20 by 60 by 25 m (length by breadth by depth) with a draft of 12 m. The added mass matrix of this island is scaled to match the dimensions of the modules considered in this case. Note that this matrix was only used for 2D (x-z plane) calculations. This means, that in this calculation only the surge, heave and pitch motion is considered.

The added mass is scaled in two steps. First, the difference in B/D ratio and size of the modules is accounted for by scaling the added mass with the equations given in table 5.2 and fig. 5.4. Second, the data is scaled with a factor 0.6 to account for the difference between 2D and 3D, as explained in section 5.2.1.

To account for the difference in B/D ratio and the size of the modules, the added mass coefficients on the diagonals of the matrix are scaled according to the following equations:

$$C_{surge} = \frac{C_{s,2} D_2^2 L_2}{C_{s,1} D_1^2 L_1} \tag{5.14}$$

Table 5.3: Sensitivity analysis to the off-diagonal added mass terms

Off-diagonal added mass	Change in natural period
10%	+3%
100%	–
200%	-8%

$$C_{heave} = \frac{C_{h,2}B_2^2 L_2}{C_{h,1}B_1^2 L_1} \tag{5.15}$$

$$C_{pitch} = \frac{C_{p,2}B_2^4 L_2}{C_{p,1}B_1^4 L_1} \tag{5.16}$$

Where C_{surge}, C_{heave} and C_{pitch} are the factors with which the added mass is scaled. The subscript 1 means based on the dimensions used for the original data and the subscript 2 means based on the dimensions of the floating GreenBattery proposed in chapter 4. C_s, C_h and C_p are the added mass coefficients for surge, heave and pitch respectively, based on the data presented in section 5.2.1.

Regarding the added mass on the off-diagonals, the scale factor is calculated as the average of the corresponding scale factors on the diagonals:

$$C_{i,j} = \frac{C_{i,i} + C_{j,j}}{2} \tag{5.17}$$

Where i and j are the row and column indices of the added mass matrix respectively, $i \neq j$ and C is the scale factor for the added mass. To see whether this way of scaling the off-diagonal added mass terms has a large influence on the outcome, a sensitivity analysis is done to the effect of a change in $C_{i,j}$ to the resulting natural periods. The result of this analysis can be found in table 5.3. From this table, it can be seen that the influence of the scale factor on the natural period is rather small, so this method for scaling the off-diagonal added mass terms seems to be sufficient. It should be noted that a reduction in the off-diagonal added mass terms leads to a slight increase in the natural period, which seems not in accordance with eq. (5.13). However, many off-diagonal added mass terms are negative in the original data, which explains this phenomenon.

Coupling stiffness

The hinged connection between the modules is modelled as a flexible connection with no stiffness in roll or pitch direction (the DOF that is left free by the hinge) and an infinitely high stiffness in the other directions, according to the Stiffness Approximation Method (SAM) described by Zhang et al. [111]. In this way, the coupling is mathematically represented by a couple of springs between the modules, therefore resulting in extra stiffness terms in the EoM.

The method of Zhang et al. [111] starts with creating a stiffness matrix with all stiffness terms of the coupling. After that, this stiffness matrix is translated to the EoMs of the separate floating modules. The stiffness matrix in a 3D case for a hinged coupling with the free DOF being roll, is:

$$K_{c,c_{pitch}} = \begin{bmatrix} K_{c,x} & 0 & 0 & 0 & 0 \\ 0 & K_{c,y} & 0 & 0 & 0 \\ 0 & 0 & K_{c,z} & 0 & 0 \\ 0 & 0 & 0 & K_{c,\theta} & 0 \\ 0 & 0 & 0 & 0 & K_{c,\psi} \end{bmatrix} \tag{5.18}$$

And for pitch as the free DOF:

$$K_{c,c_{pitch}} = \begin{bmatrix} K_{c,x} & 0 & 0 & 0 & 0 \\ 0 & K_{c,y} & 0 & 0 & 0 \\ 0 & 0 & K_{c,z} & 0 & 0 \\ 0 & 0 & 0 & K_{c,\phi} & 0 \\ 0 & 0 & 0 & 0 & K_{c,\psi} \end{bmatrix} \tag{5.19}$$

Where $K_{c,x}$, $K_{c,y}$, $K_{c,z}$, $K_{c,\phi}$, $K_{c,\theta}$ and $K_{c,\psi}$ are the connector stiffnesses in the six DoFs (surge, sway, heave, roll, pitch and yaw) respectively. If the values of these stiffnesses approach infinity, the connection can be seen as a rigid hinge [111].

These stiffness matrices can be translated to stiffness forces acting on both floating modules with:

$$K_{c,m} = L^T K_{c,c} L \tag{5.20}$$

In which $K_{c,m}$ is a 12x12 matrix with the connector stiffnesses felt by the two modules and L is a matrix including the constraints introduced by the hinge. The L matrices for a hinged connection in roll or pitch direction are given in eq. (5.21) and eq. (5.22) respectively.

$$L_{roll} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_1 & -y_1 & -1 & 0 & 0 & 0 & -z_2 & y_2 \\ 0 & 1 & 0 & -z_1 & 0 & x_1 & 0 & -1 & 0 & z_2 & 0 & -x_2 \\ 0 & 0 & 1 & y_1 & -x_1 & 0 & 0 & 0 & -1 & -y_2 & x_2 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \tag{5.21}$$

$$L_{pitch} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_1 & -y_1 & -1 & 0 & 0 & 0 & -z_2 & y_2 \\ 0 & 1 & 0 & -z_1 & 0 & x_1 & 0 & -1 & 0 & z_2 & 0 & -x_2 \\ 0 & 0 & 1 & y_1 & -x_1 & 0 & 0 & 0 & -1 & -y_2 & x_2 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \tag{5.22}$$

Where x_1, y_1 and z_1 and x_2, y_2 and z_2 are the distances in x-, y- and z-direction between the COG of the first and second module and the location of the hinged connection respectively.

When more than two floating modules are connected to each other, the $K_{c,m}$ matrix can be calculated for every hinge. Those matrices can then be combined to one matrix describing the stiffnesses of the couplings (matrix C in eq. (5.12)). First, the $K_{c,m}$ matrix should be divided in four 6x6 submatrices, one with the stiffnesses acting on module one and introduced by module one ($K_{1,1}$), one with the stiffnesses acting on module two and introduced by module two ($K_{2,2}$) and two submatrices containing the coupling stiffnesses ($K_{1,2}$ and $K_{2,1}$):

$$K_{c,m} = \begin{bmatrix} K_{1,1} & K_{1,2} \\ K_{2,1} & K_{2,2} \end{bmatrix} \tag{5.23}$$

The submatrices of every connection can now be added together. Assuming the couplings are all identical, the coupling stiffness matrix (C) for a floating island consisting of five floating modules in one row is:

Table 5.4: Added mass and hydrostatic stiffness of one module

DOF	Added mass	Stiffness
Heave	444 t	1.50 MN/m
Roll	365 tm^2	17.5 MNm
Pitch	365 tm^2	16.6 MNm

Table 5.5: Natural period of one separate floating module, SD means storage duration

Response	Wet natural period SD = 10 h	Wet natural period SD = 100 h	Dry natural period SD = 100 h
Heave	4.4	4.4 s	2.7 s
Roll	4.1	4.0 s	2.7 s
Pitch	4.2	3.9 s	2.6 s

$$C = \begin{bmatrix} K_{1,1} & K_{1,2} & 0 & 0 & 0 \\ K_{2,1} & K_{2,2}+K_{1,1} & K_{1,2} & 0 & 0 \\ 0 & K_{2,1} & K_{2,2}+K_{1,1} & K_{1,2} & 0 \\ 0 & 0 & K_{2,1} & K_{2,2}+K_{1,1} & K_{1,2} \\ 0 & 0 & 0 & K_{2,1} & K_{2,2}+K_{1,1} \end{bmatrix} \tag{5.24}$$

For islands with other arrangements, the coupling stiffness matrix can be constructed in a similar manner, while taking into account which degrees of freedom are concerned with which coupling.

In case a 2D system is considered, the equations and procedure remain the same, except for the L and $K_{c,c}$ matrices. They became for a 2D case in the x-z plane:

$$L = \begin{bmatrix} 1 & 0 & z_1 & -1 & 0 & -z_2 \\ 0 & 1 & -x_1 & 0 & -1 & x_2 \end{bmatrix} \tag{5.25}$$

$$K_{c,c} = \begin{bmatrix} K_{c,x} & 0 \\ 0 & K_{c,z} \end{bmatrix} \tag{5.26}$$

Where x_1 and z_1 and x_2 and z_2 are the horizontal and vertical distances between the COG of the first and second module and the location of the hinged connection respectively. $K_{c,x}$ and $K_{c,z}$ are the connector stiffnesses in surge and heave direction.

5.3. Natural periods of the proposed concept

Using the methodology described in section 5.2, the natural periods of the proposed concept are estimated. First, the natural periods of one separate floater are estimated. After that the natural periods of a 2D floating system (in the x-z plane) consisting of 12 modules coupled with hinges are estimated.

5.3.1. Natural periods of one floating module

Using the characteristics of the modules proposed in chapter 4, ρ_w = 1025 kg/m^3, the density of salt water ρ_{salt} = 1040 kg/m^3, the density of the acid and base ρ_{acid} = ρ_{base} = 1000 kg/m^3 and g = 9.81 m/s^2, the added mass and hydrostatic stiffness are calculated. The results for a module with a storage duration of 10 or 100 h can be found in table 5.4.

The resulting natural periods are given in table 5.5. From this table, it can be concluded that the natural periods of one module overlap with the maximum wave period. Therefore, the wave loads are regarded the most critical response. Next to that, it is necessary to investigate the natural periods of the complete island. If this results in similar natural periods, the concept dimensions must be updated, because in section 5.1 it was concluded that the natural periods and the excitation periods should not overlap to prevent resonance. Furthermore, from this table, it can be concluded that the natural period for a configuration with a storage duration of 100 h are slightly smaller compared to a storage duration of 10 h. This is mostly due to the difference in weight. Therefore, the natural periods for a storage duration of 100 h are used, because they result in the smallest periods.

5.3.2. Natural periods of 12 coupled floating modules

The natural periods of the concept presented in chapter 4 are estimated using the method described in section 5.2. Added mass data of a 2D (x-z plane) floating island consisting of 12 modules in a row was used and the natural periods of such an island were estimated, using the modules of chapter 4. The coupling stiffnesses $K_{c,x}$ and $K_{c,z}$ were set to 10^{15} N/m, as this is about eight orders of magnitude larger than the hydrodynamic stiffness of one module, see table 5.4, and therefore can be seen as rigid. Furthermore, modules with a storage duration of 100 h were used again, as these modules have a lower weight and therefore lower natural periods.

The natural periods of this floating island of 12 modules connected in a row are calculated with eqs. (5.2) and (5.13). According to Newman [72], the number of natural periods observed in such a 2D floating island should be equal to $N + 1$, where N is the number of modules. This means that in this case 13 natural periods with corresponding mode shapes are expected.

The natural periods with the corresponding mode shapes are depicted in fig. 5.5. In this figure, 14 mode shapes are given, the 13 as predicted by Newman and the rigid body surge motion with an almost infinite period compared to the other natural periods (the first mode in fig. 5.5). This almost infinite period means that there actually is no restoring force in surge direction and therefore no natural period.

From this figure, it can be concluded that the smallest natural period is 3.6 s, which is slightly smaller than the smallest natural period of one separate floater. The largest wave period expected is about 6.5s. This means that the excitation and natural periods are expected to overlap, which will cause resonance and might destruct the system. In the following sections, the parameters that influence the natural periods are investigated to discover the means to decrease the natural period of the floating island.

Furthermore, the order of the mode shapes differs from the expected order. The mode shapes with many ‘sinuses’ are expected at the smallest natural periods. For example, mode 4 and 5, with a relatively large natural period, has a mode shape that would be expected at one of the smallest natural periods. Most likely, this is due to the scaling of the added mass matrix, as further explained in section 5.5.

To investigate the influence of the correction in the added mass from 2D to 3D, fig. 5.6 gives the eigenfrequencies of the same floating island without this correction. It is expected that this will give a larger added mass, and thus lower natural periods, because water can less easily move around a 2D structure. In this case, the smallest natural period is 4.1 s, which is, as expected, larger compared to the 3D case.

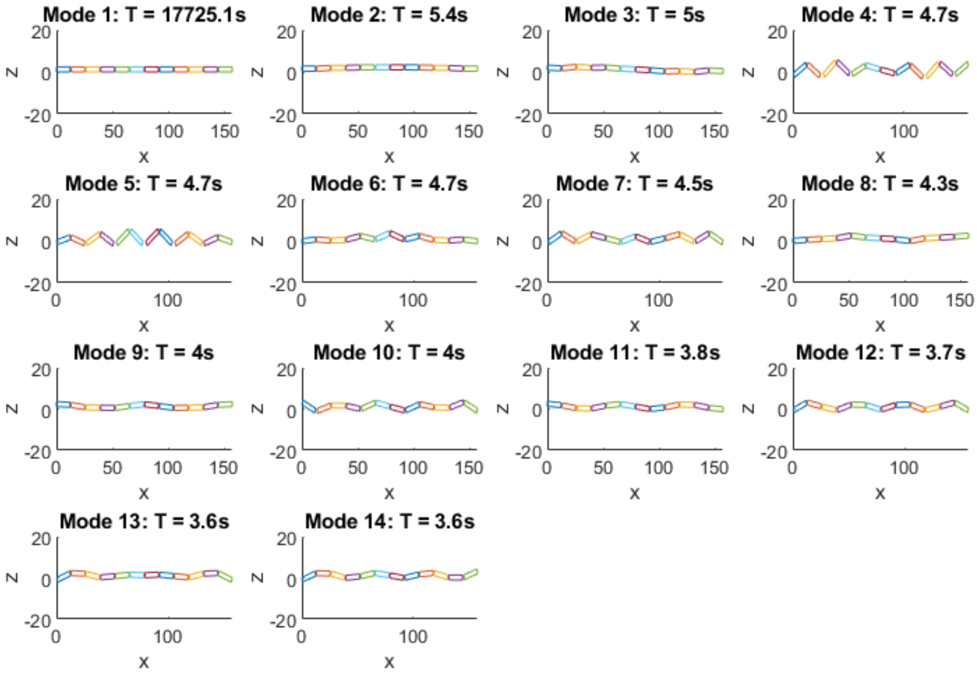


Figure 5.5: Natural period and modal shape of 12 modules hingedly coupled together

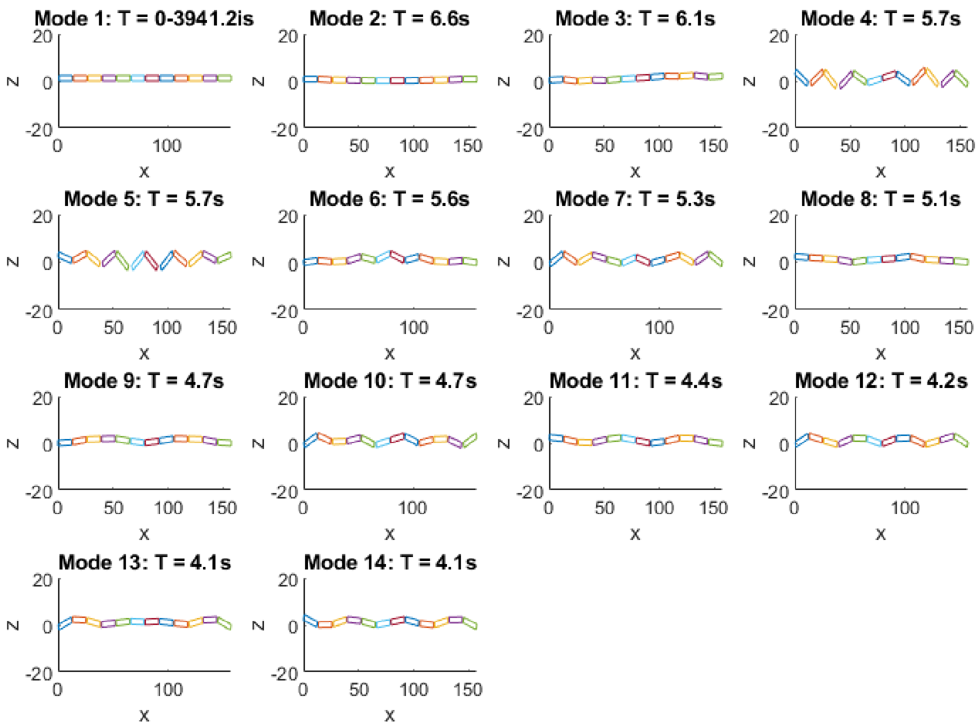


Figure 5.6: Natural period and modal shape of 12 modules hingedly coupled together without added mass correction from 2D to 3D

5.4. Parameter variation

In this section, the influence of different parameters on the smallest natural period are investigated. First, the equations in section 5.2 are reviewed, to see which parameters should have the largest influence. After that, these parameters are varied and new values are determined.

5.4.1. Parameters influencing the natural period

The natural periods of a floating system in motion is influenced by the hydrostatic stiffness and the (added) mass of the system, see eqs. (5.9) to (5.11). It should be noted that these equations are valid for separate floaters and not for floating islands consisting of different modules. Therefore, these results can not be copied directly to the case of a whole floating island. However, it gives a good indication of which parameters influence the natural period and in what way.

Combining eq. (5.4), eq. (5.9), writing the mass as the underwater volume multiplied with the water density and the added mass as a fraction of the total mass (C_a), the expression for the natural period in heave can be written as:

$$T_{Heave} = 2\pi\sqrt{\frac{(\rho_w LBD)(1 + C_a)}{\rho_w gLB}} = \sqrt{\frac{D(1 + C_a)}{g}} \tag{5.27}$$

With L, B and D the length, width and draft of the system respectively. It can be seen that the only geometric parameter with influence on the natural period in heave is the draft. Furthermore, the C_a will also decrease with increasing draft, as can be derived from table 5.2, however this decrease is smaller than the increase in draft. Therefore, a larger draft should lead to a larger natural period in heave. Furthermore, when the length is increased, the natural period is expected to increase as well, because the C_a increases.

Combining eqs. (5.5) and (5.10), taking the structure as a solid block to estimate the mass moment of inertia and writing the added mass moment of inertia as a fraction of the total moment of inertia (C_i), the natural period for roll or pitch can be calculated with:

$$T = 2\pi\sqrt{\frac{\frac{1}{12}\rho_w LBD(L^2 + H^2)(1 + C_i)}{\rho_w gLBD \cdot GM}} \tag{5.28}$$

With H the height of the floating tanks. The metacentric height (GM) is calculated with eq. (5.6) and consists of the parameters KB and KG, which are dependent on the draft and BM and GG' which are calculated using eqs. (5.7) and (5.8). Equation (5.7) can be simplified to:

$$BM = \frac{\frac{1}{12}BL^3}{LBD} = \frac{L^2}{12D} \tag{5.29}$$

Using the fact that the waterline area is rectangular, with a surface moment of inertia $I_t = \frac{1}{12}BL^3$. Assuming that $KG \approx KG$ and leaving out GG', the metacentric height can be approximated with $GM \approx BM$. Then, the following expression for the natural period can be found:

$$T \approx 2\pi\sqrt{\frac{\frac{1}{12}\rho_w LBD(L^2 + H^2)(1 + C_i)}{\rho_w gLBD\frac{L^2}{12D}}} = 2\pi\sqrt{\frac{D(L^2 + H^2)(1 + C_i)}{gL^2}} \tag{5.30}$$

Which shows that an increase in draft will lead to a larger natural period, while an increase in length

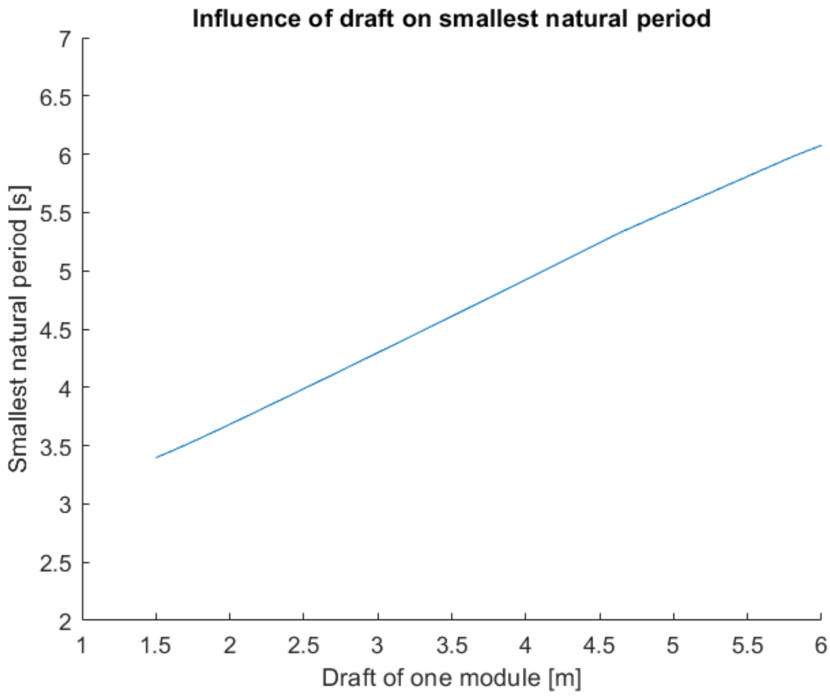


Figure 5.7: Influence of draft on smallest natural period

will have almost no effect, because a factor L^2 is found in both the numerator and denominator.

The amount of tanks within one floater directly influences the stiffness, due to the reduction in metacentric height and therefore also influences the natural period. Therefore, the amount of tanks could also be an important parameter in influencing the natural period.

5.4.2. Influence of different parameters on the natural period

This section describes the results of the parameter variation. The draft and length of the floating structure and the amount of tanks in one floater are varied to see their influence on the natural period. Furthermore, different possibilities are investigated to further increase the added mass and thus the natural periods.

Draft variation

First, the draft of the floating structure was varied, because this parameter seemed to have the largest influence on the natural periods according to section 5.4.1. An increase in draft gives a linear increase in the weight of the floating modules. This relationship was used to determine the new masses and moments of inertia of all components named in table 4.8. All dimensions in vertical direction were scaled with the same factor as the draft. Next, the natural periods of the floating island are calculated in the same manner as in section 5.3.2.

The results of the draft variation can be found in fig. 5.7. In this figure, the smallest natural period of the floating island is given for different drafts. From this figure, it can be seen that an increase in draft results in an increase in the smallest natural period. Therefore, the draft should be increased as much as possible to get better natural periods. However, the water depth in the ESL is 5 m at minimum. Next to that, some clearance between the bottom of the lake and the keel of the floating modules is needed to allow for motions of the floaters, silting and possible inaccuracies in water depth. Therefore, the new draft is set to 3 m. In this way, the smallest natural period can be increased to 4.3 s.

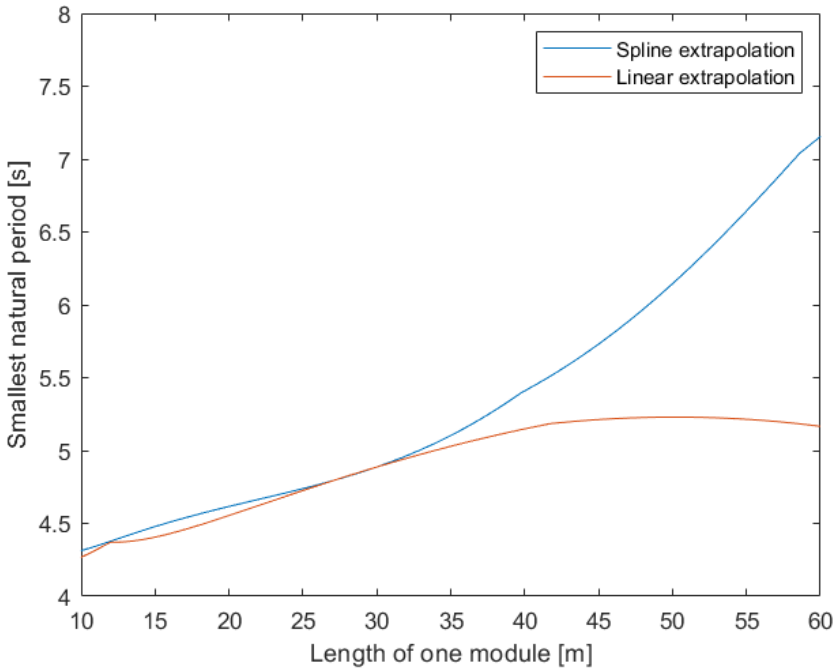


Figure 5.8: Influence of length on smallest natural period with a draft of 3m

Length variation

With the effect of the increase in draft known, the length of one module is scaled. The width of a module is scaled at the same rate as the length, to keep the modules square. The (added) mass and mass moment of inertia are also scaled with the length and width. For the added mass, the difference in B/D ratio is also taken into account.

The result of the length variation can be seen in fig. 5.8. Here, the smallest natural period is shown for different lengths and different ways of extrapolating the added mass data. For lengths larger than about 30 m, problems appeared in the calculation of the added mass, because the data in table 5.2 is only for B/D ratios up to B/D = 8. With a draft of 3 m, this means the maximum length is 24 m for reliable estimates. To estimate the natural periods for lengths larger than 24 m, the added mass data must be extrapolated. This is done using a Spline function and a linear extrapolation. The results of both methods are given in fig. 5.8. However, both extrapolation methods resulted in different added mass values as can be seen in fig. 5.9 where the results of added mass extrapolation are given. Though, the overall conclusion that can be drawn from fig. 5.8 is that an increase in length will lead to an increase in the smallest natural period. However, from this figure it is not possible to state how large the increase will be.

Although from this point of view, one floater that covers the whole lake might be the best option, it is obvious that this option is not realistic. To minimise the motions, the length of a floating body should be about 1.5-2 times larger than the largest wave length [93]. The maximum wave period in fig. 5.2 is about 6.5 s. The corresponding wave length is estimated using the dispersion relation [51]:

$$\omega_w^2 = g k_w \tanh k_w h \tag{5.31}$$

With ω_w the wave frequency in rad/s, k_w the wave number in rad/m and h the water depth. Here, the lake is assumed to be full during storm conditions (h = 22.5 m), because it is likely that the pumps

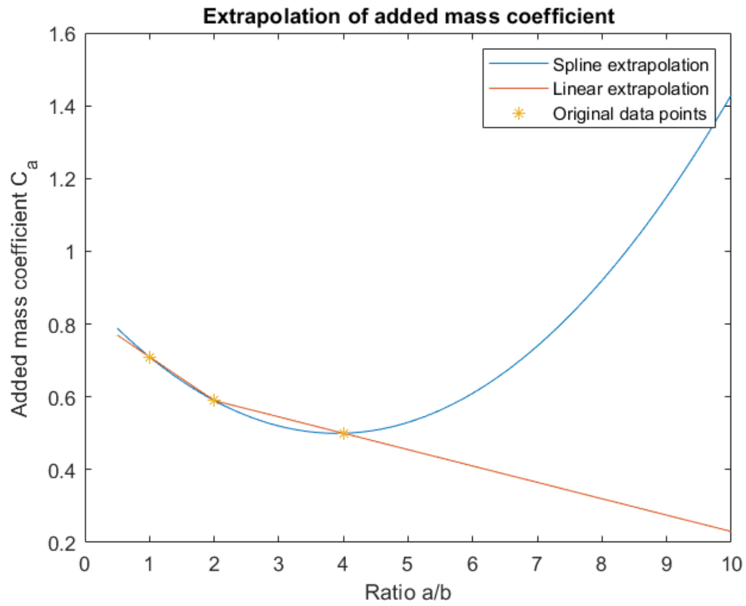


Figure 5.9: Extrapolation of added mass coefficient

are used for flood safety. k_w is solved from eq. (5.31) using the methodology described by Fenton, according to [51]. The wave length (L_w) can be calculated with [51]:

$$L_w = \frac{2\pi}{k_w} \tag{5.32}$$

For a wave with period 6.5 s, this gives a length of about 64 m. If the lake is assumed to be empty (water depth of 5 m), this results in a wave length of 42 m. Therefore, to minimise the motions, the length of one module should be about 100 m. To investigate whether it is possible to realise this length without inducing flexible body motions within one module, the characteristic length (λ_c) is calculated using [93]:

$$\lambda_c = 2\pi \left(\frac{EI}{k_c}\right)^{\frac{1}{4}} \tag{5.33}$$

With E the Young's Modulus, I the surface moment of inertia of one module in the y-z plane and k_c the hydrostatic stiffness in heave divided by the module length. Assuming that the module is sufficiently stiff if $\lambda_c = 2L$, it follows that:

$$\frac{L}{\pi} = \left(\frac{EI}{k_c}\right)^{\frac{1}{4}} \tag{5.34}$$

Which can be rewritten to:

$$L^4 k_c = \pi^4 EI \tag{5.35}$$

To calculate the surface moment of inertia, the structure of one floater is simplified to one plate at the keel and one plate at the top of the floating tanks, see fig. 5.10. The surface moment of inertia is calculated with:

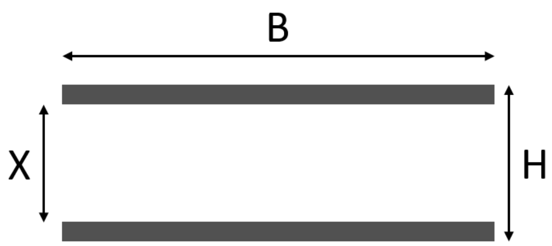


Figure 5.10: Simplified cross section (y-z plane) of one module

Table 5.6: Length of one module and required wall thickness of the tanks

Module length [m]	Plate thickness [mm]
80	2.1
100	5.1
120	11

$$I = \frac{1}{12}B(H^3 - X^3) \tag{5.36}$$

With B the width and H and X the outer and inner height of one module respectively, see fig. 5.10. Substituting this equation in eq. (5.35) results in:

$$L^4 k_c = \frac{1}{12}\pi^4 EB(H^3 - X^3) \tag{5.37}$$

To calculate the inner height, this equation can be combined with eq. (5.4) divided by L and rewritten into:

$$X = \sqrt[3]{H^3 - \frac{12L^4\rho_w g}{\pi^4 E}} \tag{5.38}$$

The required plate thickness (t) can then be calculated using:

$$t = \frac{H - X}{2} \tag{5.39}$$

In table 5.6 the required wall thickness for different lengths is given. From this table, it can be seen that for a length of 100 m, the wall thickness should be 5.1 mm to assure rigid body motions, which is achievable. Here, it is assumed that the draft of the modules is 3 m and the module height H is 4.9 m (the height of two 40 ft containers). Furthermore, the Young's modules of steel is used (E = 200 GPa).

Of course a larger length would be possible, but would increase the internal loads and therefore the price of the modules. Therefore, the length and width of one module is set to 100 m.

Variation in amount of tanks

The hydrostatic stiffness is influenced by the presence of free surfaces in the floater. The size and amount of these free surfaces can be varied to see the influence on the natural period. The results of this variation is shown in table 5.7. Here, the amount of tanks next to each other is given with the corresponding smallest natural period. Note, that all tanks have the same dimensions and the length of all tanks together equals the module length. A module length of 30 m was used, because fig. 5.8 shows that until this length the natural period can be calculated accurately, since for larger lengths, the

Table 5.7: Smallest natural period of a different number of tanks in a row for a module length of 30 m

Number of tanks	Smallest natural period
2	4.9 s
3	4.7 s
5	4.5 s

extrapolation methods are deviating.

From table 5.7 it can be concluded that the influence of the number of tanks is rather small compared to the other parameters. A reduction from 5 to 2 tanks gives an increase in smallest natural period of only 0.4 s. With a length of 100 m, the expected motions are already small, so a reduction in amount of tanks will not be necessary. Next to that, large tanks will sooner lead to problems with e.g. sloshing and when only one tank is used, the hydrostatic stiffness becomes negative.

Increasing added mass

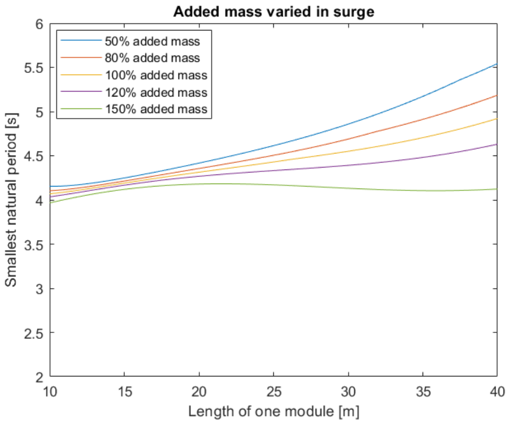
The last parameter that can be varied is the added mass. The influence of a different added mass on the smallest natural period is depicted in fig. 5.11. From these figures it can be seen that an increase in added mass leads to a small increase in natural period for heave and pitch, but a 50% increase leads to a smaller increase in natural period than the reduction in number of tanks. The surge natural period even decreases when the added mass is increased. This is due to the large number of negative added mass terms in surge direction in the added mass matrix.

In offshore engineering, the added mass is most times increased using heave plates. These are horizontal plates that are connected under or next to the floating structure. However, in this case placing heave plates under the floating structure is not possible due to the minimum water depth in the lake. Adding plates next to the structure would neither be a good option, as the size of the floaters itself could be increased just as well. Therefore, using heave plates to further increase the added mass is not a suitable option in this case. However, the added mass will be increased due to the relatively shallow water depth compared to the structure length [108].

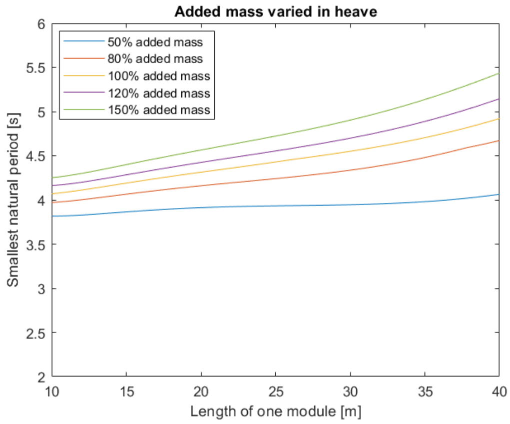
5.5. New dimensions

So, the new dimensions of one floating island should be a draft of 3 m and a length and width of about 100 m. Such an island could still be build up using the floating 40 ft containers as proposed in chapter 4, because these can be transported easily. In this way, 8 containers could be placed in the length direction, 40 in the width direction (leading to a total length and width of 98 m) and two layers of containers should be stacked upon each other to reach the necessary draft of 3 m. This leaves a freeboard of about 1.9 m (the height of one container is 2.44 m), which might not be enough to prevent green water in the most extreme case, because the maximum significant wave height expected is 1.6 m. Further analysis should be carried out to see the consequences of this also for the solar panels on deck. If necessary, the solar panels could be placed a couple of meters from the edge of the floaters or the freeboard could be increased.

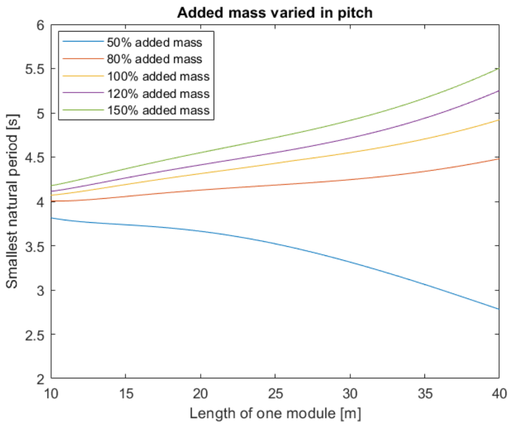
With a storage duration of 100 h, such a module can store 200 MWh of energy and a PU of 2 MW is needed per module. It is assumed that about 80% of the module can be covered with solar panels. According to Rijne Energie [36], about 1 MW_p can be placed on one hectare on land. With a peak power of 300 W_p per panel, This results in about 2700 panels per module, with a total peak power of about 800 kW_p.



(a) Variation in surge added mass



(b) Variation in heave added mass



(c) Variation in pitch added mass moment of inertia

Figure 5.11: Influence of variation in added mass on the smallest natural period

Table 5.8: Weight estimation in metric tonnes for one updated module with a storage duration of 10 h, with KG the height of the COG w.r.t. the keel

Component	Weight per unit	Amount	Weight [t]	KG [m]	I_x [10^6 kg m^2]	I_y [10^6 kg m^2]	I_z [10^6 kg m^2]	Source
Tanks	0.16 [t/m^3]	47059	7530	2.45	6042	6042	12052	[14]
Salt water	1.04 [t/m^3]	7000	7280	0.6	5850	8439	1273	
Acid + base	1.00 [t/m^3]	7000	7000	1.2	5599	619	4766	
PU	0.5 [t/kW]	14000	7000	5.9	171	115	118	
Solar panels	0.04 [t/piece]	2700	108	5.2	88	88	173	[37, 45, 92]
Connectors	50 [t/piece]	4	200	3.5	480	480	694	
Total:			29118	2.53	18229	15783	30528	

Table 5.9: Weight estimation in metric tonnes for one updated module with a storage duration of 100 h, with KG the height of the COG w.r.t. the keel

Component	Weight per unit	Amount	Total weight [t]	KG [m]	I_x [10^6 kg m^2]	I_y [10^6 kg m^2]	I_z [10^6 kg m^2]	Source
Tanks	0.16 [t/m^3]	47059	7530	2.45	6042	6042	12052	[14]
Salt water	1.04 [t/m^3]	10000	7280	0.85	8326	12025	18179	
Acid + base	1.00 [t/m^3]	10000	7000	1.7	7981	867	6809	
PU	0.5 [t/kW]	2000	1000	5.9	30	22	17	
Solar panels	0.04 [t/piece]	2700	108	5.2	88	88	173	[37, 45, 92]
Connectors	50 [t/piece]	4	200	3.5	480	480	694	
Total:			29238	1.76	22950	19528	37923	

For a storage duration of 10 h, a module can store about 140 MWh of energy for which a PU of 14 MW is needed. The storage capacity is lower in this case, because the mass of the PU increases. Therefore, less displacement is left for the liquids. The mass of one module can be found in tables 5.8 and 5.9 for an island with a storage duration of 10 and 100 h respectively. The masses and mass moments of inertia are calculated in the same manner as in chapter 4.

Four floating modules could be connected to each other to form one floating island. A schematic top view of one island is depicted in fig. 5.12. The maximum number of floating modules that can be coupled together to form one island, depends mainly on the maximum loads the connectors between the islands can resist. However, to determine this, a more sophisticated model is needed, which goes beyond the scope of this work. It is recommended for future work to do more research into this subject. The total storage capacity of one island is given in table 5.10.

The dimensions of one island are about 200 by 200 m. Keeping a clearance of 50 m between the islands, a horizontal space of 62,500 m^2 is needed per island. This means that on the lake of 20 km^2 about 300 islands can be placed. The maximum storage capacity when the whole lake is filled, is given in table 5.11.

From this table, it can be seen that the maximum storage capacity is 240 GWh for a storage duration of 100 h. However, this is larger than the expected storage need of the Netherlands in 2030, see fig. 1.2.

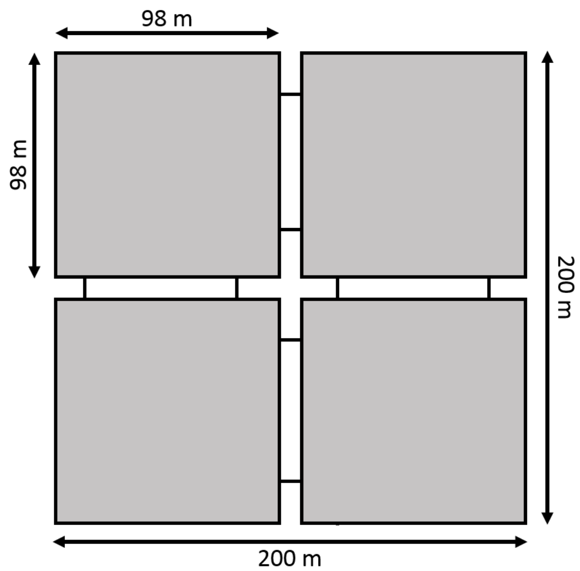


Figure 5.12: Top view of one floating island according to the new dimensions

Table 5.10: Energy and power capacity of one updated floating island

Quantity	Magnitude
Storage capacity battery	560 - 800 MWh
Power capacity battery	8 - 56 MW
Power capacity solar PV	3.2 MW_p

Therefore, it is expected that a future operator will not utilise the whole ESL. This means that space will be left for other purposes.

To see whether these changes leaded to natural periods above the wave periods, the natural periods of the proposed concept are estimated in the same manner as in section 5.3.2. An island consisting of 12 floating modules in a row was created. The available 2D added mass data of the floating island consisting of 12 modules in a row was scaled to match the new dimensions of the floating modules in the manner described in section 5.2.

However, as pointed out in section 5.4.2 the added mass data used for the scaling is difficult to extrapolate for large B/D ratios. From table 5.1 it can be seen that when the B/D ratio doubles, the added mass coefficients are decreased by an almost constant percentage. This relation is also used for extrapolating the added mass data in heave direction in table 5.2. The resulting coefficients are shown in table 5.12. When the B/D ratio doubles, the added mass coefficient reduces by about 17%. Such a trend was not observed in the added mass coefficients for surge. Therefore, they were all set to 1, so that these coefficients could not increase exponentially due to the extrapolation.

Table 5.11: Energy and power capacity of the complete system consisting of 300 floating islands

Quantity	Magnitude
Storage capacity battery	168 - 240 GWh
Power capacity battery	2.4 - 16.8 GW
Power capacity solar PV	960 MW_p

Table 5.12: Extrapolated added mass coefficients

B/D ratio	Added mass coefficient
2	0.71
4	0.59
8	0.50
16	0.42
32	0.35
64	0.30

Table 5.13: Natural period of one separate floating module with a draft of 3 m and a length of 98 m

Response	Wet natural period	Dry natural period
Heave	8.8 s	3.5
Roll	8.5 s	3.4
Pitch	8.4 s	3.1

Due to the large amount of tanks in this concept, the reduction in metacentric height GG' is neglected. The stiffness of the connectors in x and z direction was again set to 10^{20} N/m.

The resulting natural periods with their mode shapes are shown in fig. 5.13. From this figure, it can be seen that the smallest natural period is 7.3 s, which is above the largest wave period of about 6.5 s. This means that the structure should be save during its lifetime. Note however, that the added mass is not predicted in the most reliable manner possible. Therefore, it is recommended to check these results in a more sophisticated manner.

In table 5.13, the natural periods of one separate module are given. From this table, it follows that the smallest natural period of one module is in roll direction with 8.5 s. Compared to the data in section 5.3, the results are comparable, because there the smallest natural periods for one module was also slightly higher compared to the natural periods of a whole island. The dry natural period is between 3.1 s and 3.5 s. This indicates that the contribution of the added mass is large in this case, which is expected, due to the large B/D ratio. But, this also is an extra argument to check the natural periods in future work with more sophisticated models.

To examine the influence of the extrapolation of the added mass data, the natural periods and mode shapes are given in fig. 5.14, where the added mass data in heave and surge is scaled using only the data of table 5.2 and a spline function for the extrapolation. It is expected that this leads to too large natural periods, because the added mass coefficients increase rapidly for a large B/D ratio, see fig. 5.9.

From fig. 5.14, it can be seen that the smallest natural period is 11.9 s. This in indeed larger than the 7.4 s from fig. 5.13 as expected. Furthermore, the order in mode shapes in fig. 5.14 is the way they are expected to be, in contrast to fig. 5.13. The only element that is varied, is the added mass matrix. Therefore, this matrix is most likely the cause of the wrong order in modal shapes, also in figs. 5.5 and 5.6. This also stresses out the importance of checking these results with more sophisticated tools in future work.

5.5.1. Comparison to results from MARIN

The calculated natural periods are compared to data published by MARIN [75]. This data shows the motions of a floating island, which consists of 87 triangular modules connected together in seven rows. The pitch and heave Response Amplitude Operator (RAO) for each row is given for different wave

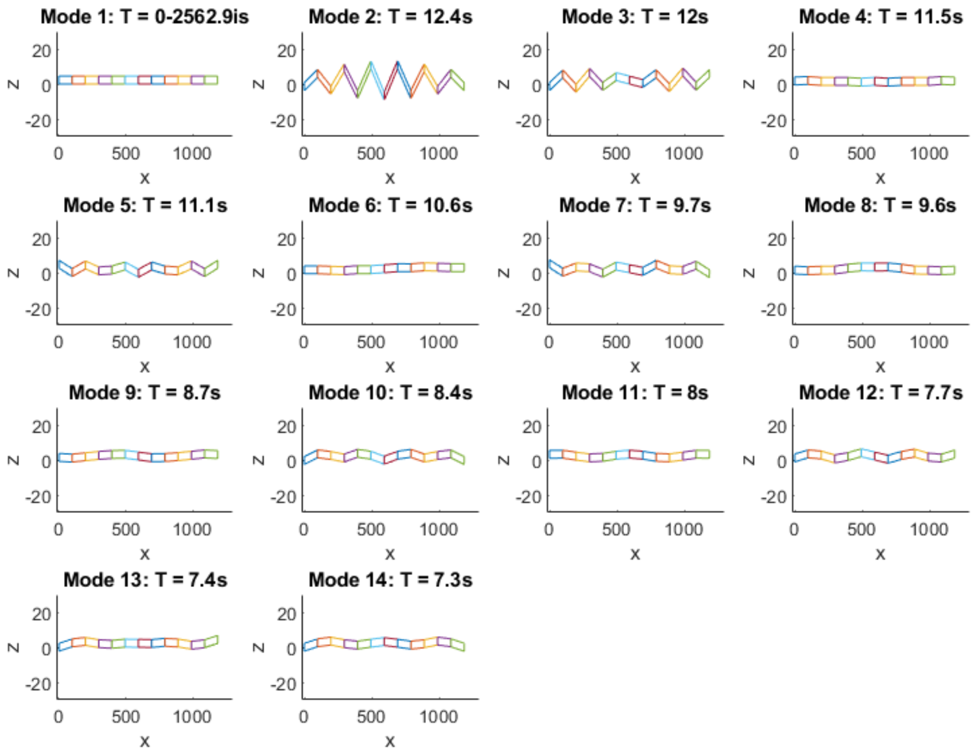


Figure 5.13: Natural periods for the modules with a draft of 3 m and length of 98 m

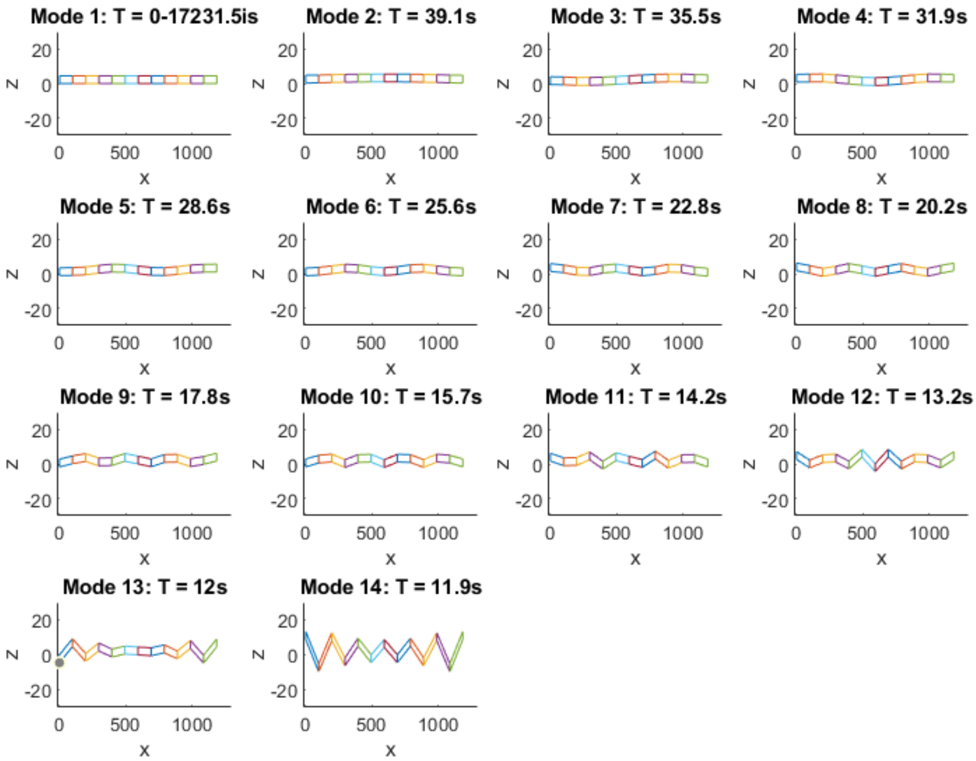
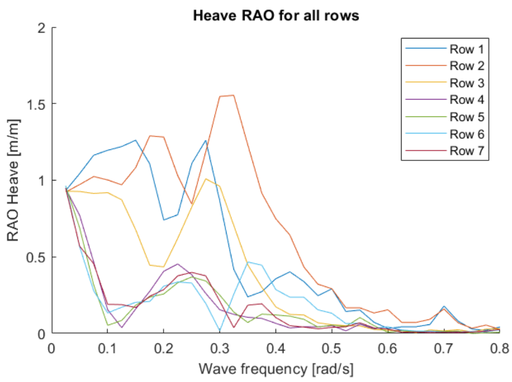
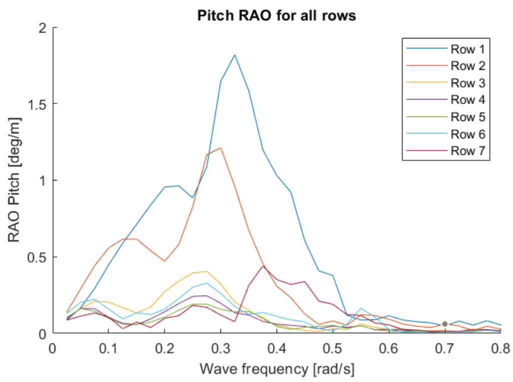


Figure 5.14: Natural periods for the floating modules with draft of 3 m and length of 98 m, based on only the available data for the added mass



(a) Heave RAO for all rows in the MARIN experiment



(b) Pitch RAO for all rows in the MARIN experiment

Figure 5.15: RAOs for the seven rows of the floating island in the experiments conducted by MARIN [75]

Table 5.14: Natural frequency of one row of the MARIN experiment [75]

Response	Dry natural frequency	Wet natural frequency	Measured natural frequency
Heave	1.1 rad/s	0.33 rad/s	0.325
Pitch	1.3 rad/s	0.52 rad/s	0.325

frequencies in fig. 5.15.

From this data, all natural frequencies of the complete island can not be determined; the response is given per row and not per mode. Though, it can be seen from [75] that the largest motion response is created in the heave and pitch motion of the first two rows at a wave frequency of about 0.33 rad/s. It is interesting to compare this frequency to the natural frequencies of one row. The modules in one row are assumed to behave like one rigid module, which is confirmed by the motions of the platform [75].

The natural frequencies of one row are calculated in the same manner as the natural periods of one module in section 5.2 and the data published by [75, 104]. The results are presented in table 5.14. From this table, it can be seen that wave frequency causing the largest response is equal to the wet natural frequency in heave direction of one row. If this conclusion is extrapolated to the floating island described in this report, the largest responses are expected to occur at a wave period of about 8.8s, see table 5.13. This means that the waves are not likely to excite the structure at a frequency which results in the largest responses. Furthermore from table 5.14, it is noted that the influence of added mass in this case is large, due to the relatively small draft of the island (B/D = 23), which is also comparable to the present study.

Maybe the most important thing to notice from the data in fig. 5.15 is that the peak in RAO with the largest wave frequency is around 0.7 rad/s. But, the height of this peak is rather small compared to the peak around 0.33 rad/s. Which means that the damping, at least in this case, is much higher for the largest natural frequencies than for the smaller natural frequencies. If this also would be the case for the floating GreenBattery, it would mean that if the smallest natural period would be excited by the waves, this would not lead to large motions. This shows that the largest wave periods expected will not cause excessive motions. Of course, this should be validated by more accurate calculations where also the damping is taken into account.

5.5.2. Connector stiffness

In this section, the influence of flexibility in the connectors in the three rotations is investigated. The connectors in the translation directions are still assumed to be rigid. This is done, because the use of only hinged connections would either restrict the island too much or allow for collisions.

To calculate the influence of the stiffnesses on the natural frequencies of a complete floating island consisting of four modules as in fig. 5.12, the method for a 3D system as described in section 5.2 is used. As no data was available for the added mass of such an island, the change in the smallest dry natural period is used to check the influence of the connector stiffnesses.

To investigate the influence of the connector stiffness in roll, pitch and yaw directions on the natural period, the stiffnesses are varied between 10^5 and 10^{20} Nm/rad. The resulting smallest natural periods are given in figs. 5.16 to 5.18. In these figures, the influence of the connector stiffness on the three smallest natural frequencies of the floating island is given. In fig. 5.16 only the stiffness in yaw direction is varied and the other rotation stiffnesses are set to 10^{20} Nm/rad. In fig. 5.17 only the roll and pitch stiffness are varied at the same time and the yaw stiffness is set to 10^{20} Nm/rad. This is done to get

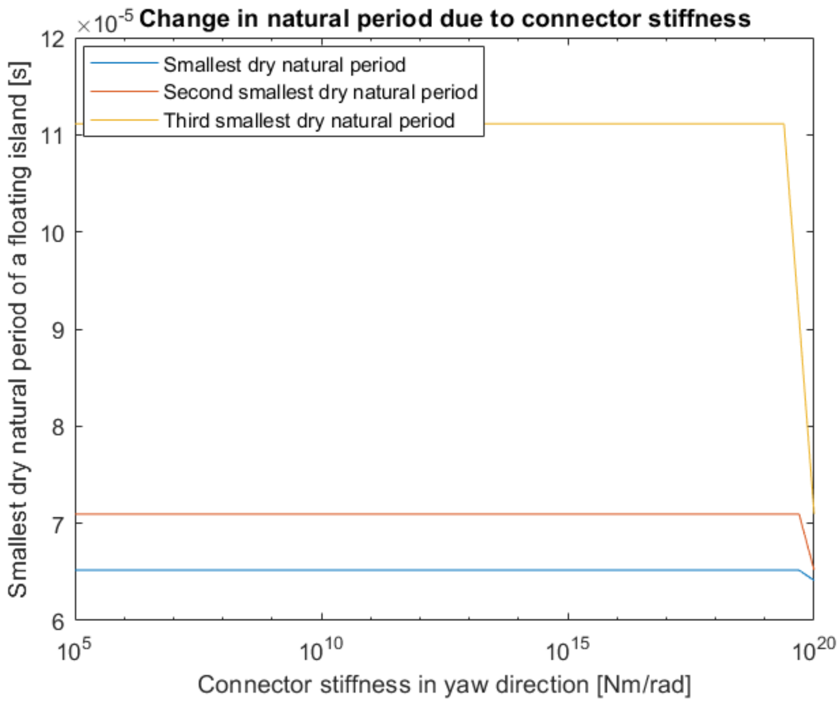


Figure 5.16: Smallest natural periods of a floating island with varying connector stiffness in yaw direction

insight in the effects of the separate motions. Finally, all rotation stiffnesses are varied at the same time, the result of which can be found in fig. 5.18.

It is expected that when the stiffness in a certain direction gets too large (it influences the natural periods and thus the mode shapes), the natural period decreases and finally goes to zero. This last case means that motions in that mode are fully restricted by the connectors, which will lead to large internal forces in the connectors. Therefore, the natural periods should not decrease due to the increasing connector stiffnesses.

From fig. 5.16, it can be seen that the three smallest natural periods are constantly about zero seconds. This means, that an island with only a rotation stiffness in yaw is restricted by the couplings and therefore can not move as it should.

When only the stiffnesses in roll and pitch direction are varied, a similar phenomenon occurs, see fig. 5.17. From this figure, it can be seen that the smallest natural period (the blue line) is always zero. This means that one DOF is restricted by the fact that the connectors do not allow for independent rotation in yaw direction. Furthermore, it can be seen that when the stiffnesses in roll and pitch direction are made larger than 10^9 Nm/rad, the second and third smallest natural periods decrease as well, which means that those modes are getting restricted.

Finally, all rotation stiffnesses are varied in fig. 5.18. Here, it can be seen that for small rotation stiffnesses the smallest natural periods are not affected. However, when the stiffnesses are increased to more than 10^9 Nm/rad, the smallest natural period starts to decrease. This is in accordance with table 5.15, where it can be seen that the hydrostatic stiffness in roll and pitch direction is almost 10^{11} Nm/rad, because the hydrostatic and connector stiffness are ‘added together’ as the total stiffness influencing the natural periods, see eq. (5.13). Therefore, the rotation stiffnesses in roll, pitch and yaw direction should not be larger than 10^9 Nm/rad. However, more research is needed to see whether this is enough to prevent collisions between the floaters.

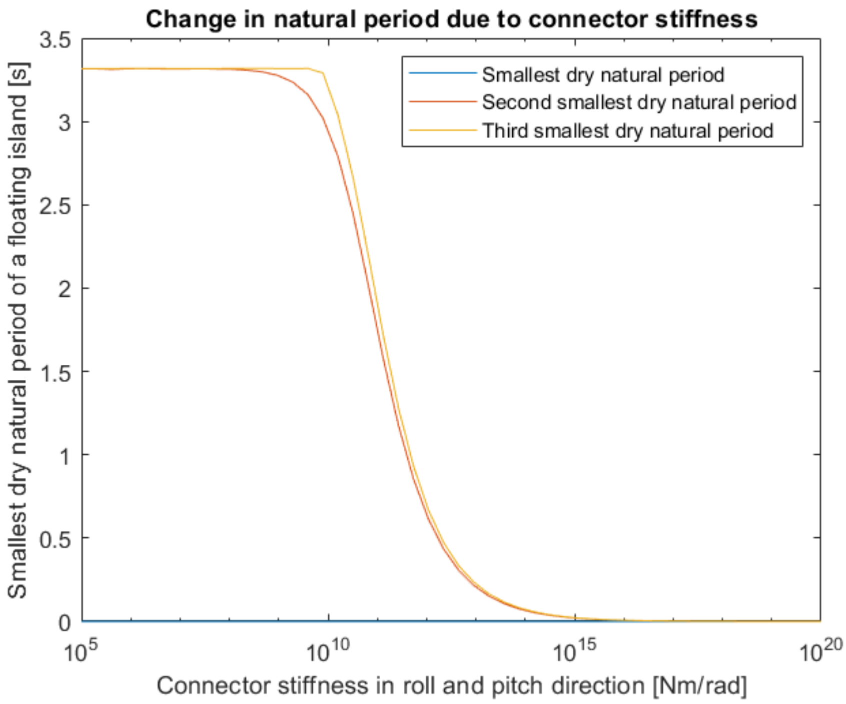


Figure 5.17: Smallest natural periods of a floating island with varying connector stiffness in roll and pitch direction

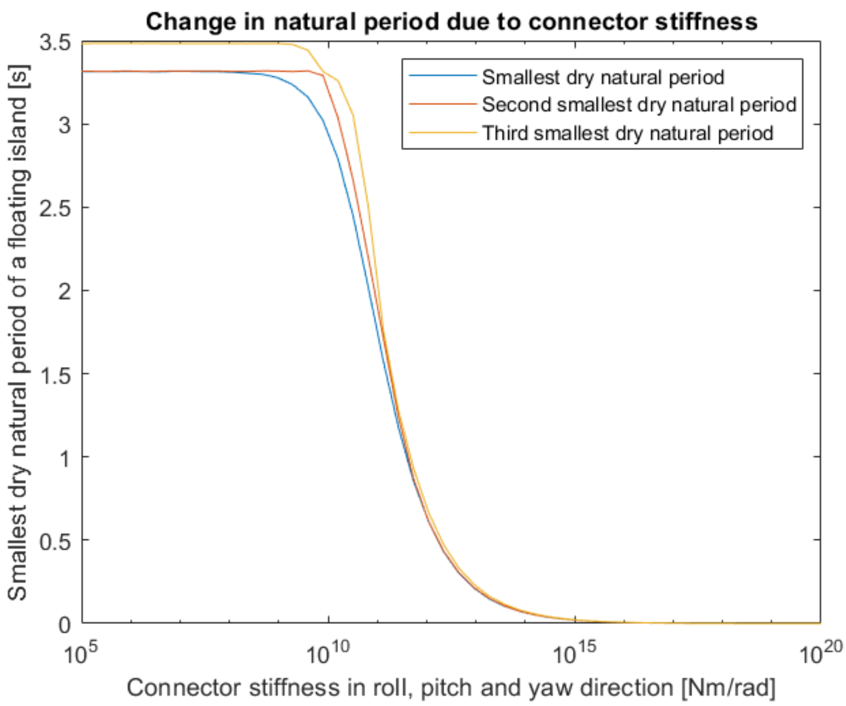


Figure 5.18: Smallest natural periods of a floating island with varying connector stiffness in roll, pitch and yaw direction. The spike at zero for the third smallest natural period is an imaginary eigenvalue

Table 5.15: Hydrostatic stiffness of one module

DOF	Stiffness
Heave	96.6 MN/m
Roll	77.3 GNm/rad
Pitch	77.3 GNm/rad

Table 5.16: Natural periods for sloshing in the tanks

Mode number n	Sloshing period
1	5.3 s
2	3.0 s
3	2.3 s

5.5.3. Sloshing

Another effect with natural period that could lead to destructive forces is sloshing in the tanks. Due to the motions of the floating island, the liquids in the tanks will move as well. According to Jung et al. [58], the periods (T_n) at which resonance occurs can be calculated with:

$$T_n = 2\pi \frac{1}{\sqrt{\frac{n\pi g}{L} \tanh\left(\frac{n\pi h}{L}\right)}} \tag{5.40}$$

Where $n = 1, 2 \ldots \infty$ are the mode numbers, g is the gravitational acceleration, L the length of the tank and h the water depth in the tank. However, it should be noted that this equation does not give the exact natural periods, because sloshing is a nonlinear effect [58]. Though, it gives good estimates. The sloshing periods for the tanks are calculated using the dimensions of one 40 ft container (a length of 12.2 m and a height of 2.4 m). The resulting periods are given in table 5.16.

From this table, it can be seen that the sloshing periods are smaller than the natural periods of the floating island itself. Therefore, sloshing is not expected to cause disastrous forces. If in later investigations is found that the sloshing period is too large, the containers could be horizontally divided into two tanks, to reduce the sloshing periods.

5.5.4. Resonance in gaps between floaters

The last effect that can cause large loads on the structure is wave resonance in the gap between the modules of a floating island. This effect is mainly dependant on the module size and spacing [91, 94]. According to Zhu et al. [112, 113], resonance happens when:

$$kL = n\pi \tag{5.41}$$

Where, k is the wave number, L the length of one module and n = 1, 2 ... ∞ are the mode numbers. The physical meaning of this equation is that if the module length equals the length of n half wavelengths, resonance is expected to occur. When n = 3, the wave period that could cause resonance is about 6.5s, the largest wave period expected. This is as expected, because the module length was chosen as 1.5 times the largest wave length.

However, the relation in eq. (5.41) is not found in other literature. Tan et al. [94] noted that the natural frequency does not only depend on the length of the floater, but also on other dimensions like the draft. Sun et al. [91] published data of experiments on the resonance in the gap between two floating bodies in close proximity. This data seems not in accordance with eq. (5.41). The largest response in [91] is seen when n equals 0.6, which is not an integer value. In this case, n = 0.6 gives a wave period larger than 6.5, which is a wave period that is not expected.

So, no simple equations are found in literature that give an accurate estimate for the wave period that causes resonance in the gap between the floating modules of an island. However, due to the presence of multiple resonance peaks [91, 112, 113] it seems inevitable that resonance will occur at some point in the gaps. This could lead to large horizontal loads on the modules and connectors. Therefore, it is recommended to carry out an analysis on this topic to investigate its consequences.

If it is found that the loads exceed the maximum capacity, the following measures could be taken: The distance between the modules could be increased, as this will lower the amplitude at resonance [91, 94]. Furthermore, the hinged connections could be replaced with flexible connections to allow for the loads to be converted to motions. Last, the freeboard could be lowered to minimise the maximum water height in the gaps and thereby the loads. However, this last option would also increase the risk of green water.

5.6. Conclusion

The most important response will be induced by the waves, because their periods are close to the natural periods of the floating island. However, the smallest natural period of the island proposed in chapter 4 is 3.6 s, which is smaller than the largest wave period of 6.5 s. Therefore, that concept will not be technically feasible.

After a parameter variation study, it was found that the dimensions of one module should be 98 by 98 by 3 m (length, width, draft). In this way the structure can be made rigid and the smallest natural period is about 7.4 s. This is above the largest wave period expected. Therefore, this concept will be technically feasible.

With these dimensions, the storage capacity of one island is 800 MWh at maximum. If the whole lake is filled with these islands a maximum storage capacity of 240 GWh can be achieved in the case of a storage duration of 100 h. This is larger than the expected needs for storage in the Netherlands in 2030. Therefore, only a part of the ESL will be needed for energy storage. The rest can be utilised in a different way.

6
Economic feasibility

In the previous chapter, a technically feasible concept was identified. In this chapter, the economic feasibility of that concept is investigated. First, the cost of the components are estimated, which are then compared to the costs of the GreenBattery on land and other EES systems. After that, the possible benefits using energy arbitrage are estimated. Next, the possible cost reductions for the floating GreenBattery are investigated. Finally, the economic advantages of combining the floating GreenBattery with a solar PV system are described. Due to confidentiality, the costs of the floating GreenBattery are not mentioned in this chapter. They are presented in appendix E, which is confidential and cannot be made public until December 17, 2022.

6.1. Costs of the floating GreenBattery

A detailed cost breakdown for the floating GreenBattery is given in appendix E. However, a simplified cost breakdown of the costs of one floating island is given in a pie chart in fig. 6.1. From this figure, it can be seen that the storage part is the most expensive with almost 75% of the costs. This storage part includes components like the floating tanks and the mooring system, because they mainly scale with the size of the storage part of the GreenBattery. The costs of the power part are significantly smaller with only about 25%. This includes the costs of the PU and the electricity cables. The costs of the solar panels form just a small portion of the total costs.

6.2. Comparison to the GreenBattery on land

AquaBattery strives to sell the power part of the GreenBattery for 1500 €/kW and the storage part for 50 €/kWh. However, the current costs of a floating island are about two to three times more expensive than based on these numbers. Therefore, the costs of the floating GreenBattery are compared to the current GreenBattery, to see where the main differences come from.

Power unit costs

As stated before, AquaBattery strives to a cost of 1500 €/kW for the power part. This power part is assumed to be the same for the floating GreenBattery as for a GreenBattery on land. However, for a floating GreenBattery, a floating electricity cable is required. This cable is more expensive than a

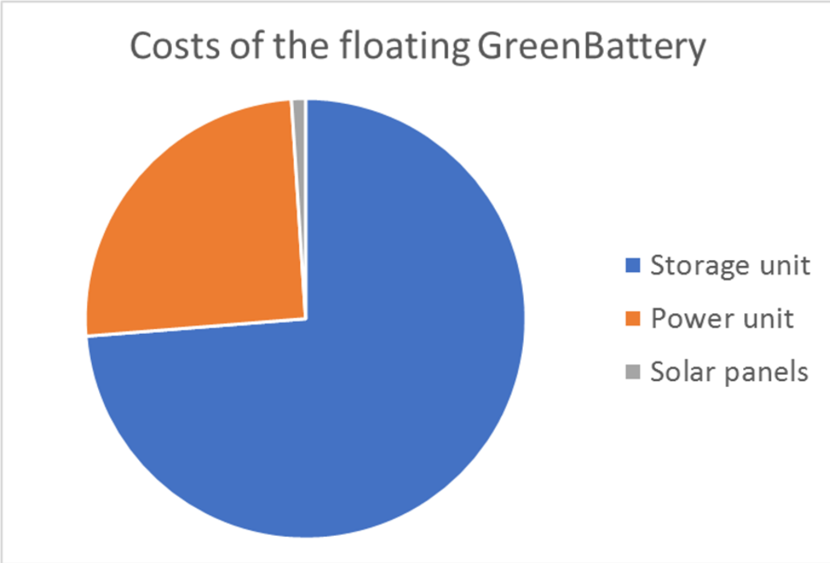


Figure 6.1: Cost breakdown for the floating GreenBattery

cable on land. Therefore, the power part of the floating GreenBattery will be slightly more expensive compared to the GreenBattery on land.

In order to reduce these costs, the PU could be placed on land, relieving the need for floating electricity cables. Next to that, the PU would be more easily accessible for maintenance. Though, this also means that no solar panels can be placed on top of the floating tanks, because they make use of the electricity cables as well. Furthermore, in this case a pipeline network will be needed between the floating tanks and the PU, which introduces other costs and could decrease the efficiency of the GreenBattery due to an increase in the required pump power. Last, the costs of the electricity cables are relatively low compared to the other components, see appendix E. So, in this case, placing the PU on land would not be a good option, because of the combination with solar panels. However, in case the combination with solar PV is unwanted, a more detailed analysis should be carried out to value the different arguments.

Costs of storage part

The target costs of the storage part for the GreenBattery is about 50 €/kWh. However, the storage part of the floating GreenBattery is more expensive due to the expensive floating tanks it consists of. These tanks are placed in a harsher environment compared to onshore tanks and are therefore more expensive. One floating 40 ft container costs about €40,000 according to Ravestein Container Pontoons [14], while a normal 40 ft container used for transport would cost about €3000 to €3500 [13]. Second hand containers are for sale for about €1000 per container [13]. Next to that, mooring lines are needed to keep the floating tanks in place. Potential cost reductions to decrease the costs of the storage part are discussed in section 6.5, however floating tanks will always be more expensive than land based tanks, because they operate in a harsher environment.

Rent of water area

Another difference in costs between the GB on land and on the Delta21 lake is land or water rent. According to Delta21, the rent on water will be around 20,000 €/km^2 per year, while the rent for land area is normally about ten times larger. However, tanks on land can be build much higher than the floating tanks of this concept. For example, the Maasvlakte Olie Terminal in the Port of Rotterdam has tanks with a height of 22.5 meters [102]. For a floating GreenBattery this height could only be realised in deeper waters, like the open sea. This means that this floating GreenBattery needs about 5 times more space than the GreenBattery on land. Therefore, the rent of water area is about twice as expensive for the GreenBattery on land. However, for the whole lake, this is a difference of about €400,000 per year, which is just a small portion of the investment costs.

In conclusion, it can be stated that the floating GreenBattery is more expensive than the GreenBattery on land. This is mainly caused by the floating tanks, which are about 12 times more expensive than normal 40 ft containers. Therefore, cost reductions for the floating GreenBattery are required. When this is achieved, the floating GreenBattery could become equally attractive as the GreenBattery on land, if the water area can be rented for free or when the maximum draft is large enough.

6.3. Comparison to other energy storage systems

To get a better insight in required size of the cost reduction, the costs of the floating GreenBattery are compared to other EES systems. Herefore, the method described by Zakeri and Syri [110] is used, in which they used the Levelised Cost Of Storage (LCOS) to compare the costs of different EES systems. The LCOS is calculated by dividing the annualised Life Cycle Costs (LCC) per kW by the total amount of stored energy in one year per kW of power.

$$LCOS = \frac{C_{LCC,a}}{nh} \tag{6.1}$$

With $C_{LCC,a}$ the annualised LCC per kW, n the number of full cycles per year and h the storage duration of the EES system. The annualised LCC are calculated with:

$$C_{LCC,a} = C_{cap,a} + C_{O\&M,a} + C_{R,a} + C_{DR,a} \tag{6.2}$$

Where $C_{cap,a}$ represents the annualised Capital Expenditure (CAPEX) per kW, $C_{O\&M,a}$ the annual operation and maintenance costs per kW, $C_{R,a}$ the annual replacement costs per kW and $C_{DR,a}$ the annualised disposal and recycling costs per kW. The latter three are assumed to be 5% of the CAPEX in total, while the annualised CAPEX is calculated with:

$$C_{cap,a} = C_{cap}CRF \tag{6.3}$$

With C_{cap} the total CAPEX per kW and CRF the Capital Recovery Factor (CRF), see eq. (6.5). The CAPEX per kW is calculated with:

$$C_{cap} = C_p + C_s h \tag{6.4}$$

With C_p the cost of the power part per kW and C_s the cost of the storage part per kWh. The CRF is calculated using:

$$CRF = \frac{i(1+i)^T}{(1+i)^T - 1} \tag{6.5}$$

Where i is the interest rate and T the expected lifetime of the EES system.

According to Zakeri and Syri [110], the total costs of the energy delivered by the EES system, the Levelised Cost Of Energy (LCOE), is calculated by adding the charging costs divided by the efficiency to the LCOS:

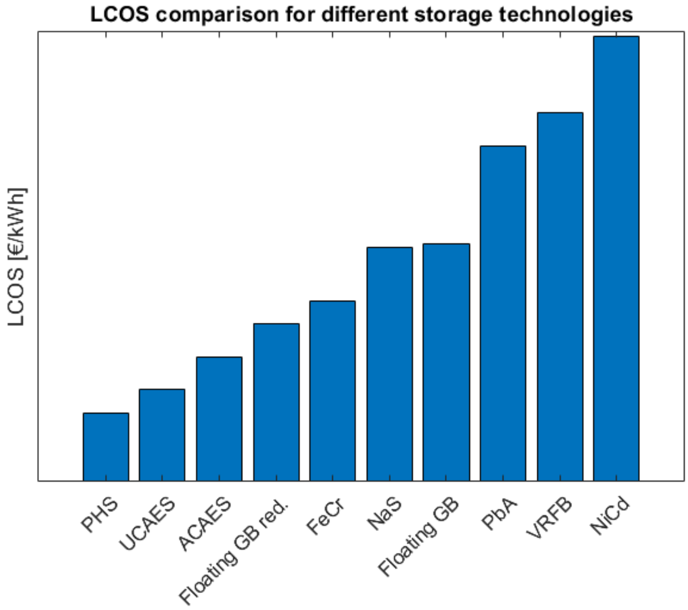


Figure 6.2: Comparison of the floating GreenBattery to other EES systems based on LCOS, Floating GB red. is the floating GreenBattery with reduced costs, data from Zakeri and Syri [110]

$$LCOE = LCOS + \frac{C_{ch}}{\eta_{sys}} \tag{6.6}$$

With C_{ch} the charging costs per kWh and η_{sys} the efficiency of the EES system.

Based on the numbers presented in appendix E, a storage duration of 24 h and 150 cycles per year, the LCOS of the floating GreenBattery is estimated to be between 0.20 - 0.25 €/kWh. This number is compared to other EES systems, to investigate the attractiveness of the floating GreenBattery.

This comparison is based on data published by Zakeri and Syri [110]. The results are depicted in fig. 6.2. The data in this figure is based on a storage duration of 8 h and 250 cycles per year. A complete figure is presented in appendix E. From this figure, it can be seen that the LCOS of the floating GreenBattery is comparable to the more expensive EES systems. When the costs are reduced with the measures presented in section 6.5, the floating GreenBattery is cost competitive with most of the EES systems. However, the other EES systems are more difficult to place on the ESL, due to physical constraints like for PHS or because of the toxicity like in the case of PbA. When these systems are placed on water, this will result in larger costs.

However, this comparison is only valid for a storage duration of 8 h, while the focus in this thesis is on long term storage with a storage duration of 10 to 100 h. Van de Vegte [97] published data of the annualised costs of different EES systems, based on the CAPEX and charging price. The annualised costs are calculated in the same manner as for the LCOS. However, it is not calculated per kW, but for the storage needs presented in fig. 1.2. The results are presented in fig. 6.3. Again, a complete figure can be found in appendix E. In this figure, also the costs of a conventional gas turbine are presented. It should be noted that a gas turbine is not an energy storage system, but it can be used to deliver energy in periods of a shortage of electricity. In this case, curtailment would be used when there is a surplus of renewable energy.

From fig. 6.3, it can be seen that the floating GreenBattery is indeed one of the more expensive EES

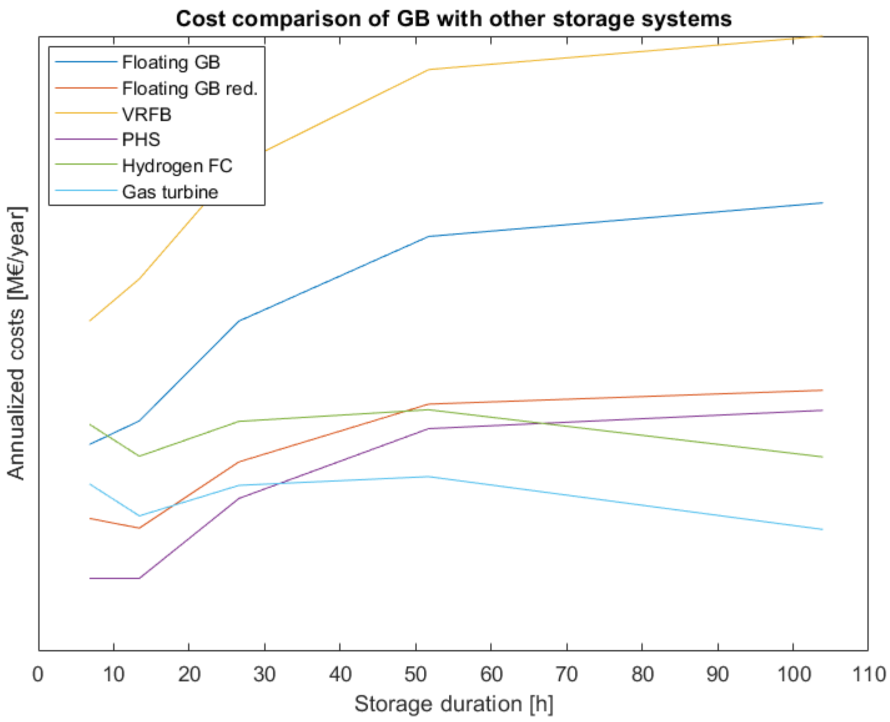


Figure 6.3: Comparison of the floating GreenBattery to other EES systems based on the annualised costs, Floating GB red. is the floating GreenBattery with reduced costs, data from van de Vegte [97]

systems. It is less expensive than the VRFB, but most likely this is partially due to the difference in expected lifetime for the GreenBattery and the VRFB and the fact that no operation and management costs were taken into account. Furthermore, from this figure it becomes clear that energy storage using a PHS system or a hydrogen fuel cell will be more cost effective compared to a floating GreenBattery, because their annualised costs are smaller. It can be seen that a hydrogen fuel cell is more expensive for a short storage duration, but when the storage duration increases, hydrogen becomes less expensive. This is because the storage part of hydrogen costs only about 13 €/kWh [73], which is just a small part of the cost of the storage part for the floating GreenBattery. When the costs of the floating GreenBattery are reduced using the measures presented in section 6.5, the costs become more comparable to the other EES systems, although PHS is less expensive in any case.

6.4. Benefits of an energy storage system

In terms of economic feasibility, the costs of the floating GreenBattery is just one side of the coin. The other part is determined by the benefits or revenues of the system. For an energy storage system, the revenue is mainly based on the fluctuations in the electricity price. The battery is charged when the price is low and discharged when the price is high [98]. This process is called energy arbitrage. According to Van Egmond [98], the average maximum difference between the highest and lowest price in the German electricity grid in 2015 was 0.064 €/kWh. Of course, not all electricity can be sold with this price difference, because it takes time to discharge a battery. For now, it is assumed that the current average difference between the buying and selling price is about 0.05 €/kWh. However, in the future, this difference may increase due to the increasing penetration of variable RES in the electricity grid, which causes a larger mismatch between the supply and demand of electricity. According to Groot, the fluctuations in electricity price will be between 0.15 and 0.25 €/kWh by 2030.

When these numbers are compared to the LCOS of the floating GreenBattery of about 0.20 - 0.25 €/kWh, it can be concluded that with the current electricity price, it is not possible to generate a sound business case based on only energy arbitrage. When looking at the future electricity prices, the costs and benefits are almost equal, which means that it will be difficult to generate a profit. Therefore, a cost reduction is necessary for the floating GreenBattery.

Of course there are other possibilities to generate a benefit with an EES system. One example is removing the need for grid reinforcement. In this case, an EES system is placed in an area with large fluctuations in the supply and demand of electricity, to level out the fluctuations instead of having to reinforce the local grid to be able to deal with the fluctuations. However, it is difficult to state how large these benefits are in the Delta21 scenario and how it shares around the different EES systems present in the Delta21 plan. The floating GreenBattery has societal benefits as well, as mentioned in section 1.3. This should be investigated in future work.

6.5. Potential cost reduction for the floating GreenBattery

As shown in section 6.1, the storage part, including the floating tanks are the most expensive part of the system. Therefore, the main focus of the cost reduction is on reducing these costs. The ways to reduce these costs are introduced in the coming paragraphs.

In chapter 3 concepts with floating bags as a storage medium were proposed. The main advantage of these concepts was that floating bags are expected to be cheaper compared to rigid floaters. Though, they were not chosen mainly because their reliability has not been demonstrated yet. Therefore, more research should be done to see whether those floating bags can be used instead of the rigid tanks, to decrease the costs.

However, a less sophisticated, but maybe also less effective cost reduction could be achieved when the floating 40 ft containers are replaced with (second-hand) tank barges. More details on the cost reduction achievable in this way can be found in appendix E.

Another possibility to indirectly reduce the costs of the storage tanks is to increase the energy density of the storage medium. This can be achieved in two ways. First, more research should be done to increase the energy density of the GreenBattery. Second, other types of salt that can store more energy could be used instead of the sodium chloride used in the GreenBattery. Though, in this second option, care should be taken not to use toxic chemicals, as that would mean a thread to the aqueous life in case of a leak. Next to that, this could also affect the other components and their costs, making the cost reduction more questionable.

Although reducing the costs of the storage part will have the largest impact, reducing the costs of the power part will also reduce the total costs. To achieve this, more research should be done to power unit. The main part of the power unit is the membranes. Therefore, more research should be done to make these membranes less expensive and stronger. When they are made less expensive, this directly reduces the costs. Next to that, if they are made stronger, the power density will increase. In this way, a smaller power unit can be used on the floating islands, thereby reducing the costs of the power part.

For now, the question is, which cost reduction is feasible to achieve with the floating GreenBattery. As pointed out, the costs of the floating tanks could be reduced by replacing the tanks with tank barges, more information on this cost reduction can be found in appendix E. Another possibility is to do more research to the GreenBattery itself and try to increase the energy density. The energy density of the

GreenBattery is currently expected to be around 10 kWh/m^3. However, AquaBattery pointed out that in theory an energy density up to 20 kWh/m^3 should be achievable. This means that in this way the costs of the storage part could be halved. In total it is expected that the costs of the storage part could be reduced with 75 up to 85%. With these cost reductions the LCOS of the floating GreenBattery can be reduced to 0.10 - 0.15 €/kWh. The more exact values can be found in appendix E.

These costs are smaller than the expected benefits of 0.15 - 0.25 €/kWh. Therefore, it will be possible to make an economically feasible concept for the floating GreenBattery based on only energy arbitrage. Of course, there are also other possible sources of income, as mentioned in section 6.4. These can further increase the economic feasibility of the floating GreenBattery.

6.6. Benefits of the extra solar PV system

The main advantage of the combination of the floating GreenBattery with a solar PV system is that the same space in the ESL is double used. Next to that, the electricity generated with the solar panels can be stored in the GreenBattery and sold at a higher price. This section describes the advantages of adding a solar PV system to the floating GreenBattery. To quantify the advantages, an average price of 850 €/kW$_p$ is assumed for a floating solar PV system. This is based on cost estimates of the World Bank Group [46]. An exchange rate of $1 = €0.85 is assumed in this section.

First, there is the advantage of sharing the rent costs of the lake surface. As stated in section 6.2, the rent cost for the lake are about 20,000 €/km^2 per year according to Delta21. With a separate floating solar PV system, the rent costs would be about twice as much, because for both the GreenBattery and the solar PV system rent would need to be payed. On one km^2 of lake area, about 15 islands can be placed with a total installed capacity of 48 MW$_p$ of solar panels. This means a reduction in costs of 0.42 €/kW$_p$ per year.

An other advantage is cable pooling, because the solar PV system can use the same electricity cable as the GreenBattery. As described in section 6.1, a floating electricity cable costs about 90 €/kW. Assuming the power of the GreenBattery and solar PV system are equal (this depends on the storage duration), a cost reduction of 90 €/kW is achievable.

The inverter for the GreenBattery and the solar PV system can be combined into one. According to Acharya and Devraj [2] and the World Bank Group [46], the costs for the inverter account for about 8% of a floating solar PV system, which means about 70 €/kW$_p$. Assuming that the inverter of the GreenBattery can also be used for the solar PV system without drastically increasing the costs, 70 €/kW$_p$ can be saved.

Because the solar panels are placed directly on the tanks, no extra floaters are needed. Though, a mounting system comparable to on land solar panels is needed. This leads to a cost reduction of about 45 €/kW$_p$ [46].

This means that the total cost reduction due to the combination of the floating GreenBattery with solar panels is about 205 €/kW$_p$ at maximum (cables, inverters and floaters). This corresponds to almost 25% of the costs of a regular floating PV system. If the whole lake is filled with floating islands (960 MW$_p$ of solar panels in total), a total of 197 M€ can be saved. However, compared to the total investment, this means a relatively small reduction.

Other cost reductions could be in the costs for net integration, executing maintenance at the Green-Battery and solar PV system at the same time and in the design and construction costs. However, these are not quantified in this study.

The main advantage of this combination in terms of benefits is that the electricity can be stored and sold at any time, which means also at times with the highest electricity price. However, this means that the LCOS of the floating GreenBattery should be the smaller than the difference in electricity price, which is the case according to section 6.5.

Thus, the cost reduction by the combination of the floating GreenBattery with a solar PV system is most beneficial for the solar PV system itself, because the reduction in costs is almost 25% of the total costs for a floating solar PV system. However, when the cost reduction is compared to the costs of the floating GreenBattery, the reduction is relatively small. This is because a floating solar PV system uses rather cheap floaters, while for the floating GreenBattery expensive floating tanks are needed. Combining both leads to a reduction of the cheap floaters of the floating solar PV system. Therefore, from a cost reduction perspective, it could be more beneficial to combine the floating GreenBattery with a system that uses a comparable floater. This could be a VLFS, like a floating airport of town, but more investigation is needed to confirm this statement.

7 Conclusion

In this study, a concept design for an additional Electrical Energy Storage (EES) system on the Energy storage Lake (ESL) of Delta21 was generated based on the GreenBattery of AquaBattery. Based on a stakeholder analysis, design objectives were set up, which were used in a multi criteria analysis to investigate which concept design is most suitable. A technical feasibility assessment of this concept led to an update in the chosen design. Finally, the economic feasibility of this concept was analysed. The following conclusions can be drawn from this study.

Most feasible concept design

Using a multi-criteria analysis based on a set of design objectives, the most feasible concept was chosen. This concept consists of rigid floating storage tanks for storing the liquids of the GreenBattery with a Power Unit (PU) and solar panels on top. Multiple floaters can be connected to each other in two rows of modules using hinged connections to form one floating island. Such an island is moored to the bottom of the lake using flexible mooring lines.

This concept was chosen, because of its reliability compared to concepts using flexible floating tanks. Furthermore, solar panels can easily be placed on top of this concept, while for a concept with submerged storage tanks, this would be impossible. Next to that, a floating concept is expected to be cheaper than a concept with submerged storage tanks.

The design objectives were established using a stakeholder analysis. This analysis showed that the most important stakeholders are AquaBattery, Delta21 and the future operator of the battery system. AquaBattery wants the concept to be technically and economically feasible and to comply with the regulations. The main interest of Delta21 is to combine the GreenBattery with a solar PV system to multiuse the ESL and to make an economic feasible concept. The future operator is still unknown, which makes it difficult to state their precise requirements. Therefore, the characteristics of the GreenBattery were made scalable, which is mostly represented by the scalability of the final concept. Furthermore, the required storage duration was chosen to be scalable between 10 and 100 hours and a storage capacity in the GWh scale is wanted. On the basis of this stakeholder analysis, design objectives and requirements were set up.

To generate a concept design that complies best to these design objectives and requirements, the morphological chart method was used to systematically explore the solution space. First, a function analysis was carried out to explore what the concept should be able to do. The functions that were found, can be summarised in three groups: House the components of the GreenBattery on the ESL, keep the GreenBattery on its place and connect it to the grid.

Next, for every function, the possible solutions were investigated. These solutions were then combined to form possible concepts. In total ten concepts were set up. Four of those concepts used underwater basins for storing the salt water, while the other six were based on floating tanks.

Technical feasibility

The wave excitation turned out to cause the most important response. Therefore, the criterion to test the technical feasibility of the proposed concept was that the natural periods of the floating island are not allowed to overlap with the expected wave periods, to prevent resonance. The expected wave peak period during a storm with a 100 year return period is between 2.7 and 4.2 s. Using a JONSWAP spectrum, the largest wave period expected turned out to be about 6.5 s.

A parameter variation study was done to see the influence of different parameters on the natural periods. The draft and length turned out to have the largest influence on the natural periods. Therefore, the draft was increased to 3 m, the maximum possible in the ESL, and the length was increased to 100 m, which is about 1.5 times the maximum wave length. The influence of the number of tanks on the natural periods turned out to be rather small. Increasing the natural periods using heave plates is not possible due to the restricted draft. With these dimensions, one island is built up using two rows of two modules. One module consists of two layers of 8 by 40 floating 40 ft containers, resulting in overall dimensions of 98 by 98 by 4.9 m (length by width by height), which serve as the floating tanks. A maximum of 300 of these islands can be placed on the ESL. This results in a maximum storage capacity of 168 - 240 GWh for a storage duration of 10 and 100 h respectively. The peak power of the solar PV system is estimated at almost 1 GW_P.

These floater dimensions result in natural periods between 7.4 and 12.5 s, which do not overlap with the expected wave frequencies. Furthermore, according to experimental data of floating islands published by MARIN, the damping at the smallest natural periods is large. Therefore, an excitation at the smallest natural frequencies will not result in large motions. This means that with the new dimensions of the floating island, this concept is technically feasible.

It turned out that when the island is connected with only hinges, the island has either too many or too few degrees of freedom. Therefore, rotational springs are added in the remaining rotation directions. The stiffness of these springs should not exceed 10^9 Nm/rad, because this would influence the smallest natural periods of the islands too much.

The last item checked in the technical feasibility are the sloshing periods in the tanks. These turned out to be 5.3 s at maximum, which means that they are smaller than the expected natural periods. Therefore, the tank dimensions are regarded right.

Economic feasibility

To investigate the economic feasibility of the proposed concept, the costs of the concept are compared to other EES systems using the Levelised Costs Of Storage (LCOS). For the floating GreenBattery, the LCOS turned out to be between 0.20 and 0.25 €/kWh. This is comparable to the more expensive EES systems. Therefore, a cost reduction is necessary, to make the floating GreenBattery more competitive with other EES systems.

The possible benefits of an EES system are expected to be 0.15 - 0.25 €/kWh by 2030 based on only energy arbitrage. These benefits are comparable to the LCOS of the floating GreenBattery. Therefore, it will be difficult to generate a sound business case without a cost reduction.

This cost reduction can be achieved by replacing the floating containers with (tank) barges or large pontoons and by increasing the energy density of the GreenBattery. In this way, a cost reduction of about 75 up to 85% is achievable in the costs for the floating tanks. Furthermore, the use of stronger and less expensive membranes in the PU could reduce the costs of the power part. With these cost reductions, the LCOS of the floating GreenBattery can be reduced to about 0.10 - 0.15 €/kWh. These costs are smaller than the expected benefits and comparable to the costs of the less expensive EES systems. Therefore, the floating GreenBattery will be economically feasible and it is worth it to work out this concept in more detail.

The combination of the floating GreenBattery with solar panels led to a reduction in costs of about 205 €/kW$_p$ of solar panels, which means almost 0.7 M€ per island, compared to two separate systems. This cost reduction is achieved in the costs for electricity cables, inverters and the floaters. Therefore, the combination of a floating GreenBattery with a solar PV system is advantageous.

7.1. Recommendations

This thesis described a concept design for a GreenBattery on the ESL of Delta21. The following items could be investigated in future work.

Recommendations for the concept design

- The requirements of the operator, like the final storage duration and storage capacity of the battery system, should be defined once the operator is known. This is required for a final design.
- A new mooring design should be made, taking into account the new module dimensions. The preliminary design proposed by Marine Flex uses too many mooring lines, which would unnecessarily increase the installation costs. Furthermore, the mooring system should be designed in such a way that the distance between the islands is minimised, to make maximal use of the lake possible.
- The influence of the floaters on the aquatic life in the ELS should be investigated and the results should be considered in further design stages. Next to that, it would be interesting to look at how this concept can improve the aquatic life. Maybe, the floaters could be used as a natural habitat for the creatures living in the ESL or the floaters could be multi used for aquaculture. This would contribute to SDG 14, life below water.
- The use of this concept on other waters like rivers or seas should be investigated. In this way, this concept can be sold more than only once. Furthermore, it could potentially enlarge the energy storage capacity of the (Dutch) waters.
- It would be interesting to investigate whether the seawater could be used in the GreenBattery instead of the salt water in the tanks. In this way, about twice as much energy could be stored in the same floater, because the salt water tanks are not needed any more.

Recommendations for the technical feasibility

- Using more sophisticated models, a more accurate prediction of the natural periods of the floating island should be made. During this thesis available added mass data was scaled to the dimensions of the proposed concept. However, the resulting mode shapes are in the wrong order. This indicates that the added mass should be calculated in a more precise manner. Using this model, the motions of the island should be predicted as well.

- The size of one floating island should be investigated. This is dependent on the internal forces on the connectors, which could not be predicted in this analysis.
- The floating tanks within one module need to be interconnected to allow for a similar concentration. However, the effect of this on the hydrodynamic stiffness and the sloshing periods should be investigated. From this, it will follow how large the openings between the tanks can be and how many tanks should be coupled together.
- Maximum values for the connector stiffnesses were determined, but the final value should be decided. Here, care should be taken that the modules cannot collide.
- Another effect with a natural period is the mooring system. This is not investigated yet, because the characteristics of the final design are still unknown. During the design of this system, the natural period should be determined not to overlap with the excitation frequencies of wind, waves and currents.
- Wave resonance in the gaps between the modules can occur. This phenomenon should be investigated in more detail, because it can cause large forces on the connectors. Furthermore, resonating waves could lead to green water on deck. Therefore, also the available freeboard should be checked.

Recommendations from the economic analysis

- Further cost reduction can be achieved in multiple ways. First, more research should be done to increase the energy and power density of the GreenBattery. Next to that, the possibility to use (second hand) tank barges or other large floating pontoons should be worked out in more detail. Also, floating bags for the liquid storage should be investigated further, because they potentially could decrease the investment. Furthermore, the potential for using this concept with other EES systems that store the electricity in liquids and have a higher energy density than the GreenBattery should be investigated. Though, care should be taken that the costs are not increased at other points, like the power unit, and the liquids should be safe to use on water. Last, the energy density and costs of the PU should be decreased by e.g. doing more research to stronger and cheaper membranes.
- The social and economic value of placing the GreenBattery on the ESL should be investigated in more depth. These include first of all, delivering energy to the pumps of the ESL in case these pumps are used for the water safety. Furthermore, the GreenBattery could provide a backup for the Port of Rotterdam or the region Rotterdam or could be used to smooth out the generation of renewable energy for e.g. the production of green hydrogen. The GreenBattery could fulfil multiple functions at the same time, thereby increasing its value.
- To maximise the output of the solar PV system, it could be interesting to combine this concept with a solar tracking system. Further research should be done to investigate the effectiveness of this possibility.
- The advantages of other possibilities for multiuse of the floating GreenBattery should be investigated. For example, it could be more beneficial to combine the floating GreenBattery with a floating airport or town.

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A

Wind and wave conditions

This appendix gives more information on the wind characteristics and the calculation of the wave conditions.

A.1. Wind characteristics

The wind characteristics are given in fig. A.1. They are made with data from waveclimate.com [107], for location 52°00' N, 03°40' E.

A.2. Calculation of the wave conditions

According to Holthuijsen [51], the wave conditions can best be estimated using the method introduced by Young and Verhagen [109]. The significant wave height (H_{m_0}) can be calculated based on the dimensionless significant wave height ($\tilde{H}_{m_0}$, see eq. (A.1)), which can be calculated using eq. (A.2).

$$H_{m_0} = \tilde{H}_{m_0} \frac{U_{10}^2}{g} \tag{A.1}$$

In which g is the gravitational constant and U_{10} is the wind speed at $10m$ above still water level.

$$\tilde{H}_{m_0} = \tilde{H}_{\infty} \left(\mathbf{tanh} \left(k_1 \tilde{F}^{m_1} \right) \right)^p \tag{A.2}$$

With $\tilde{H}_{\infty}$, k_1, m_1 and p being constants, whose values are given in table A.1 and $\tilde{F}$ the dimensionless fetch, see eq. (A.5).

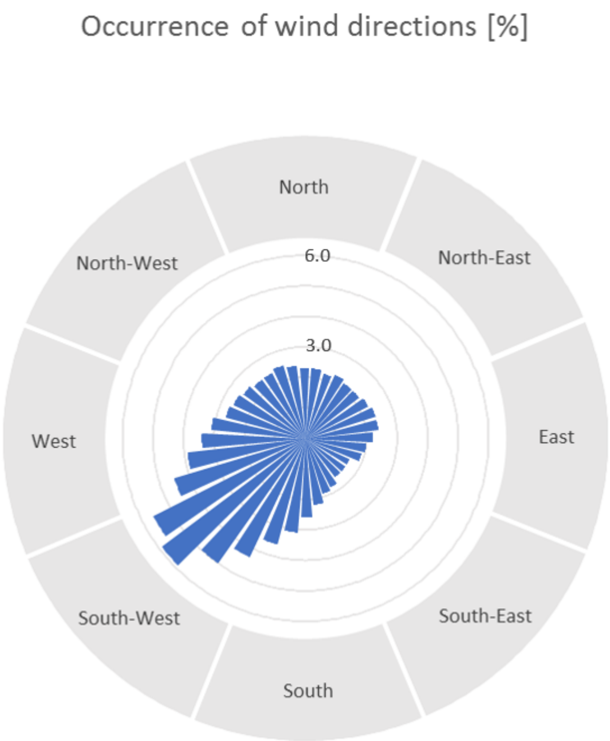
The peak period of the wave spectrum (T_p) can be calculated using the dimensionless period ($\tilde{T}_p$, see eq. (A.3)), which can be calculated using eq. (A.4).

$$T_p = \tilde{T}_p \frac{U_{10}}{g} \tag{A.3}$$

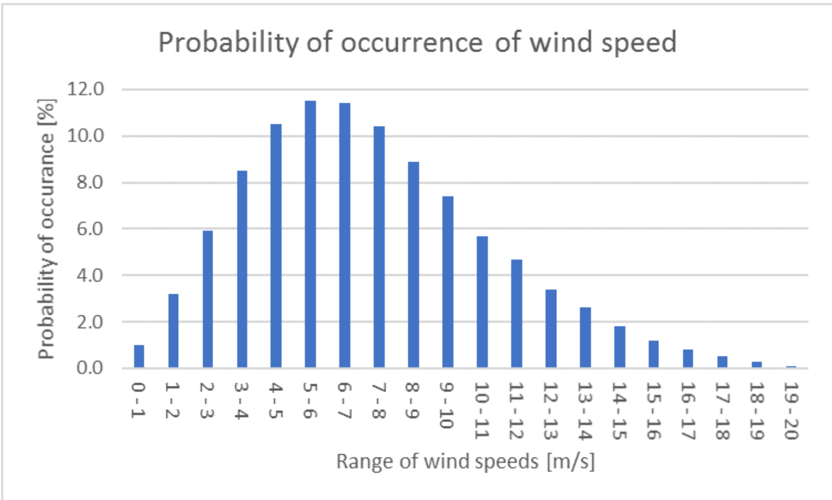
$$\tilde{T}_p = \tilde{T}_{\infty} \left(\mathbf{tanh} \left(k_2 \tilde{F}^{m_2} \right) \right)^q \tag{A.4}$$

With $\tilde{T}_{\infty}$, k_2, m_2 and q again being constants, whose values are given in table A.1.

The dimensionless fetch can be calculated using eq. (A.5).



(a) The probability that the wind comes from a certain direction



(b) The probability of occurrence of a certain wind speed

Figure A.1: The predominant wind direction and speed based on a scatter table of waveclimate.com [107]

Table A.1: The values of the constants used for the calculation of the wave height and peak period according to [51]

Constant	Value	Constant	Value
$\tilde{H}_\infty$	0.24	$\tilde{T}_\infty$	7.69
k_1	$4.14 \cdot 10^{-4}$	k_2	$2.77 \cdot 10^{-7}$
m_1	0.79	m_2	1.45
p	0.572	q	0.187

$$\tilde{F} = F\frac{g}{U_{10}^2} \tag{A.5}$$

In which F is the fetch in meters. The maximum fetch possible in the ESL is about $5km$. However, if the lake is filled with floating units, less waves will be generated. The exact influence of floating units on the wave growth can not be calculated yet, because the final layout of the concept in the ESL is not known yet. Therefore the fetch is varied between 1 and 5 km as a first guess to capture the influence of floating units if they will be present. Once the final layout of the concept in the ESL is known, its influence could be estimated in the same manner as the influence of ice floes on wave growth is estimated (A.J.H.M. Reniers, personal communication, May 26, 2020). Masson and LeBlond [70] and Wadhams et al. [105] described methods to do this, however to include this, is not part of this thesis.

With the peak period and significant wave height know, the wave spectrum can be calculated. According to Holthuijsen [51], this can best be done using the JONSWAP spectrum introduced by Hasselmann et al. [49]. Though, it should be noted that the JONSWAP spectrum is based on the deep water assumption.

The JONSWAP wave spectrum ($E_{JONSWAP}(f)$) is calculated with:

$$E_{JONSWAP}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right] \gamma^{\exp\left[-\frac{1}{2}\left(\frac{f/f_{\text{peak}}-1}{\sigma}\right)^2\right]} \tag{A.6}$$

With f the wave frequency, α the energy scale parameter, g the gravitational acceleration (g = 9.81 m/s^2) and γ and σ are shape parameters. α is calculated using:

$$\alpha = 0.0317\tilde{f}_{peak}^{0.67} \tag{A.7}$$

With $\tilde{f}_{peak} = 1/\tilde{T}_{peak}$ the dimensionless peak frequency, γ = 3.3 and σ = 0.07 for $f \leq f_{peak}$ and σ = 0.09 for $f > f_{peak}$.

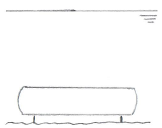
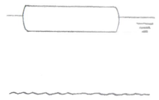
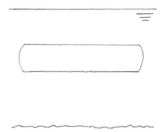
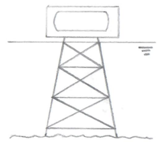
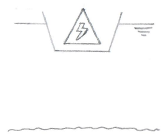
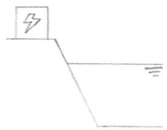
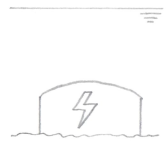
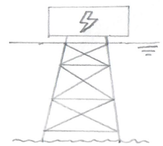
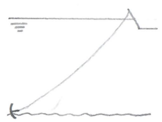
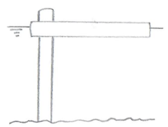
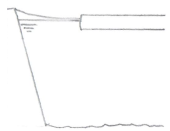
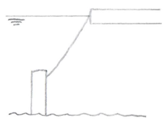
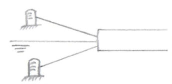
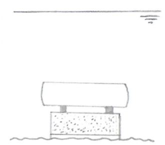
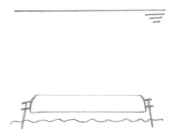
B

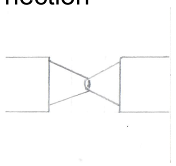
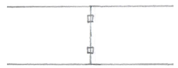
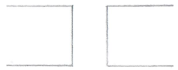
Morphological Chart

In this appendix, the more detailed results of the concept generation are presented. First, the Morphological Chart (MC) is presented. After that, the ten concepts set up using the MC are presented as a combination of the solutions of the MC.

The MC is given in table B.1. In this table, all sub-solutions to the different functions are summarised. In the left column, the functions are given, while in the row behind a function the solutions are presented. Note, the table is stretched over two pages.

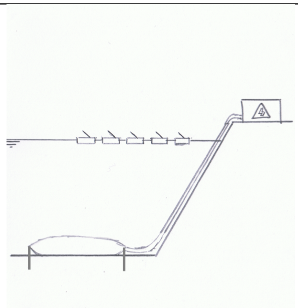
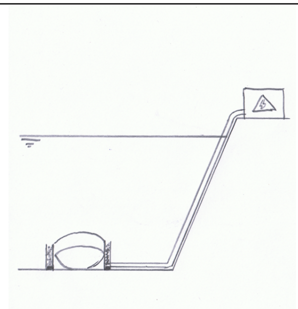
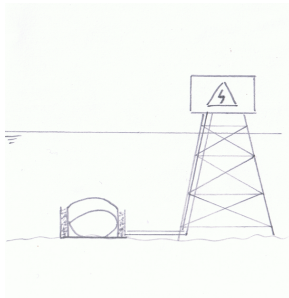
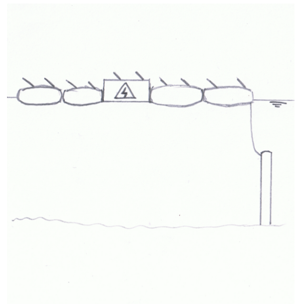
Table B.1: Morphological chart for the design of a GreenBattery on water. Note, the table is extended over two pages

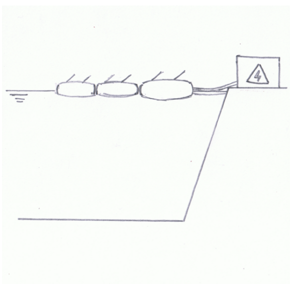
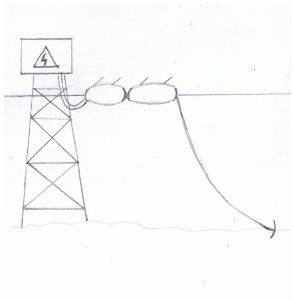
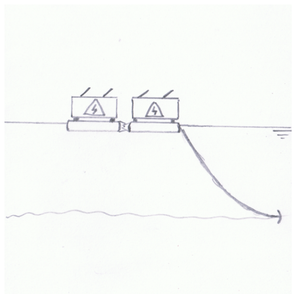
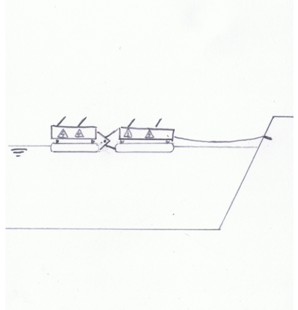
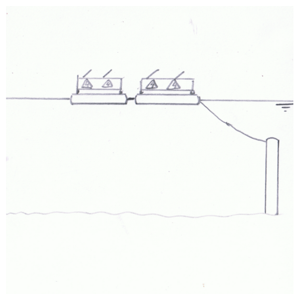
Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7
Carry liquids (location)	On lake bottom 	Floating 	Submerged 	Above water 	Artificial lagoon		
Carry liquids (tank type)	Flexible tank	Rigid tank	Bag in container	Dikes			
Carry power unit	Floating 	Onshore 	Submerged 	Above water 			
Connect tanks/ stacks	Rigid pipe	Flexible pipe	Hinged pipe				
Carry solar panels	On top of the GreenBattery	Separate system	No solar PV system				
Fasten to ground	Mooring lines to seabed 	Pile restrained anchoring 	Mooring lines to shore 	Pile with rope 	Winch system 	Gravity based 	(Suction) piles 

Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7
Connect modules	Hinged connection 	Flexible connection 	Flexible connection with hinges	Direct connection 	No connection 		
Connect to grid	Fixed cable	Flexible cable					
Connect solar PV and power unit	Flexible cable	Fixed cable	No connection				

The ten concepts are explained table B.3. In the first column of this table, the functions are listed. The other columns contain the used solutions to the functions per concept. Note, the table is stretched over two pages.

Table B.3: The 10 concepts depicted per function

Concept	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Carry liquids (location)	On lake bottom	On lake bottom	On lake bottom	On lake bottom	Floating
Carry liquids (tank type)	Flexible tank	Bag in container	Bag in container	Flexible tank	Flexible tank
Carry power unit	Onshore	Onshore	Above water	Above water	Floating
Connect tanks and power unit	Rigid pipe	Rigid pipe	Rigid pipe	Rigid pipe	Flexible pipe
Carry solar panels	Separate system	No solar PV	No solar PV	No solar PV	On top of GreenBattery
Fasten to ground	(Suction) piles	Gravity based	Gravity based	(Suction) piles	Pile with rope
Connect modules	No connection	No connection	No connection	No connection	Direct connection
Connect to grid	Fixed cable	Fixed cable	Fixed cable	Fixed cable	Flexible cable
Connect solar panels and power unit	Flexible cable	No connection	No connection	No connection	Flexible cable
Picture					

Concept	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10
Carry liquids (location)	Floating	Floating	Floating	Floating	Floating
Carry liquids (tank type)	Flexible tank	Flexible tank	Rigid tank	Rigid tank	Rigid tank
Carry power unit	Onshore	Above water	Floating	Floating	Floating
Connect tanks and power unit	Flexible pipe	Flexible pipe	Rigid pipe	Rigid pipe	Rigid pipe
Carry solar panels	On top of GreenBattery	On top of GreenBattery	On top of GreenBattery	On top of GreenBattery	On top of GreenBattery
Fasten to ground	Mooring lines to shore	Mooring lines to seabed	Mooring lines to seabed	Mooring lines to shore	Pile with rope
Connect modules	Direct connection	Direct connection	Hinged connection	Hinged connection	Flexible connection
Connect to grid	Fixed cable	Fixed cable	Flexible cable	Flexible cable	Flexible cable
Connect solar panels and power unit	Flexible cable	Flexible cable	Fixed cable	Fixed cable	Fixed cable
Picture					

C

Selection criteria

In this appendix, the selection criteria used in chapter 3 are further explained. In the first section, the requirements used to evaluate the design objectives are defined. The second section explains the weights given to the criteria.

C.1. Requirements

For the evaluation of the different concepts, the performance of the concepts to the requirements is estimated on a scale of 0 to 2. A score of 0 means that the concept poorly fulfils the requirement, while a score of 2 means almost perfect agreement with the requirement. The definition of the scores are given in table C.1 for each requirement.

Table C.1: Definition of the evaluation of the requirements. Note, this table extends over three pages

Objective	Requirement	How to evaluate?	Weight	Reason
Safe	Low risk of drowning during activities	Relative estimation: 0: High risk; 1: Medium risk; 2: Low risk	0.5	Chance and impact
	Little installation / maintenance work requiring manpower	0: (almost) everything with manpower; 1: about half with manpower; 2: (almost) nothing with manpower	0.5	Chance and impact
Environmentally friendly	Small chance of leakage	0: most failure points; 1: medium failure points; 2: almost no failure points	0.33	Chance and impact
	Small amount of acid / base in one reservoir	Relative estimation: 0: largest tanks; 1: medium tanks; 2: smallest tanks	0.34	Chance and impact
	Use of environment friendly materials	0: (almost) no environment friendly materials; 1: half of materials environment friendly; 2: (almost) all materials environment friendly;	0.33	Effect on global environment less than on local environment
GreenBattery	Easy volume measurement	0: Flexible tank; 2: rigid tank;	0.1	Always possible, but more difficult for flexible tanks
	Easy conductivity measurement	Not evaluated	0	Always possible
	Scalability of power/ energy ratio	0: Difficult to adjust; 1: Moderately difficult to adjust; 2: Easy to adjust;	0.6	Important characteristic of the GreenBattery
	Not decrease efficiency	0: Large influence on efficiency; 1: Small influence on efficiency; 2: No influence on efficiency;	0.3	Mainly influenced by concept design

Objective	Requirement	How to evaluate?	Weight	Reason
ESL	Resistant against wind speeds (max. 31m/s)	0: Rough surface above water; 1: flat surface above water; 2: Nothing above water;	0.2	Environmental loads are evaluated the same
	Resistant against waves (max H_{m0} = 1.5m)	0: Above water and sensitive for waves; 1: Above water, not sensitive for waves; 2: Under water;	0.2	Environmental loads are evaluated the same
	Resistant against currents (max 1m/s)	0: NEITHER streamlined NOR robust concept; 1: Streamlined OR robust concept; 2: Streamlined AND robust concept;	0.2	Environmental loads are evaluated the same
	Little horizontal space needed for anchoring	0: More than 2/3 of horizontal space for mooring; 1: About 1/s of horizontal space for mooring; 2: (almost) no space required for mooring;	0.2	Environmental loads are evaluated the same
	Deal with different temperatures (-15C to 40C)	0: Difficult to deal with temperature range; 1: Moderately difficult to deal with temperature range; 2: Easy to deal with temperature range;	0.07	No data available for GreenBattery and temperature differences
	Least deterioration over time	0: Exposed to and sensitive for UV-light AND marine growth; 1: Exposed to and sensitive for UV-light OR marine growth; 2: Exposed to and sensitive for NEITHER UV-light NOR marine growth;	0.13	Smaller weight than environmental loads, because it depends on the concept design

Objective	Requirement	How to evaluate?	Weight	Reason
Low CAPEX	Low component costs	0: uses most expensive components; 1: Uses some expensive components; 2: Uses (almost) no expensive components;	0.6	Largest part of cost
	Easy installation	0: (almost) always expensive material required; 1: Sometimes expensive material required; 2: (almost) no expensive material required	0.25	Installation costs are expected to be less than component costs
	Good transportability	0: (almost) all components require special transport; 1: Half of components fit on lorry; 2: (almost) all components fit on lorry;	0.15	Transportation costs are expected to be less than installation costs
Low OPEX	Easy maintenance access	0: Components under/ on water; 1: Components under water/ on land; 2: Most components reachable over water;	0.5	Chance and impact
	Little maintenance required	Relative estimation: 0: Often maintenance required; 1: Sometimes maintenance required; 2: (almost) no maintenance required	0.5	Chance and impact
Reliable energy storage	Empty reservoirs easy in motions	0: Motion sensitive reservoir; 1: Some motion sensitiveness; 2: Fixed reservoir;	0.6	More critical case
	Reliable components	Relative estimation: 0: Many unreliable components; 1: Some unreliable components; 2: Reliable components	0.4	Less critical case
Multiuse: Solar PV	Cost effective combination with solar PV	0: Not possible to integrate with GB; 1: Integrated on flexible floater; 2: integrated on rigid floater;	1	

Table C.3: Conversion of average scores to requirements to objective scores

Average score to requirements (x)	Score to objective
0 ≤x < 0.4	0
0.4 ≤x < 0.8	1
0.8 ≤x < 1.2	2
1.2 ≤x < 1.6	3
1.6 ≤x ≤2	4

To calculate the final score of a concept to an objective, the weighted average score of the requirements belonging to one objective is calculated. Using this score, 0 to 4 points are given to each objective, according to table C.3. In this table, the average scores to the requirements are given in the left column and the corresponding scores for the objectives in the right column.

C.2. Weights of the criteria

This section gives a short explanation on why certain objectives are regarded more important than others. For each branching in the objectives tree, the relative importance of the branches is discussed.

Societal – Technical – Economic objectives
From these three branches, the economic objectives are regarded most important, because if the concept would not be economically viable, no one would invest in it. The technical objectives are regarded more important than the societal objectives, because in this stage of design, the technical objectives have a larger influence on the performance of the concept. The societal objectives are more important to consider during the detailed design.

Low cost – High benefits
The benefits will be more or less the same for every concept. However, the costs will vary due to the differences between the concepts. Therefore, 'Low costs' is regarded more important than 'High benefits'.

Requirements from GreenBattery – ESL
The requirements from the ESL are regarded the most important technical objective, because this indicates which system will be able to withstand the environmental conditions best. The requirements from the GreenBattery concern with the performance of the GreenBattery and are therefore regarded less important than the requirements from the ESL.

Environment friendly – Safe
Environment friendly is regarded the most important objective of this branching, because it contains requirements that are set by politics. The safety objective is of course important as well, but plays a bigger role in the detailed design.

Reliable energy storage – Combine with solar PV
The combination with solar PV is more important than a larger reliability; a larger reliability will only slightly increase the benefits, while a solar PV system will increase the benefits by adding an extra income source. Next to that, the combination with solar PV is one of the objectives of the client Delta21 and is therefore given extra importance.

Low OPEX – Low CAPEX

The OPEX for a GreenBattery on land is currently estimated to be about 20% of the total costs. Of course, this will be slightly different for a GreenBattery placed on water, because carrying out maintenance to a GreenBattery on a lake will be more expensive. However, it is expected that the CAPEX will still be the largest part. Next to that, at this stage of design, the estimation of the CAPEX will be more reliable compared to the estimation of the OPEX. Therefore, the CAPEX is given a higher weight than the OPEX.

D

Evaluation of the concepts

This appendix treats the more detailed results of the concept evaluation. The first section treats the evaluations that are not described in chapter 3. The second section describes the evaluations on the requirement level.

D.1. Results of the comparisons

This section describes the results of the MCAs that are not described in chapter 3, but are mentioned in fig. 3.4. These include the choice between concepts with submerged, rigid storage tanks (concepts 3 and 4), concepts with submerged, flexible storage tanks (concepts 1 and 2), concepts with rigid or flexible storage tanks and concepts with floating, flexible storage tanks (concepts 5, 6 and 7). These MCAs are described in the coming subsections.

Concepts with submerged, rigid storage tanks

The MCA for the concepts with submerged, rigid storage tanks is given in table D.1. From this analysis it can be concluded that concept 4 is better than concept 3. This is because concept 4 will be cheaper to build, due to the PU that is located on land in stead of on a platform in the lake. Next to that, performing

Table D.1: MCA of concepts with submerged, rigid storage tanks

Criteria	Weights	Concept 3	Concept 4
Safe	0.06	1	3
Env. Friendly	0.09	2	2
GreenBattery	0.08	2	2
ESL	0.18	2	2
CAPEX	0.25	0	4
OPEX	0.11	1	2
Reliable storage	0.10	2	2
Solar PV	0.14	2	2
Total:	1	1.33	2.56

Table D.2: MCA of concepts with submerged flexible storage tanks

Criteria	Weights	Concept 1	Concept 2
Safe	0.06	3	1
Env. Friendly	0.09	2	2
GreenBattery	0.08	2	2
ESL	0.18	2	2
OPEX	0.11	2	1
CAPEX	0.25	4	0
Reliable storage	0.10	2	2
Solar PV	0.14	2	2
Total:	1	2.56	1.33

Table D.3: MCA of concepts with submerged rigid versus flexible storage tanks

Criteria	Weights	Concept 1	Concept 4
Safe	0.06	2	2
Env. Friendly	0.09	1	2
GreenBattery	0.08	2	2
ESL	0.18	2	3
CAPEX	0.25	4	2
OPEX	0.11	1	3
Reliable storage	0.10	1	3
Solar PV	0.14	2	2
Total:	1	2.21	2.38

maintenance in a building on land is safer than on a platform in the lake. More information on this MCA can be found in table D.6.

Concepts with submerged flexible storage tanks

The MCA for the concepts with submerged, rigid storage tanks is given in table D.2. This analysis shows that concept 1 will be a better choice than concept 2. The reason for this is the same as for the evaluation between concept 3 and 4, namely the PU is located on land, which makes it cheaper to build and easier and safer to maintain. More information on this MCA can be found in table D.5.

Concepts with submerged storage tanks

To make the choice between concepts with submerged storage in either rigid or flexible tanks, concepts 1 and 4 are compared to each other using the MCA given in table D.3. This analysis shows that concept 4 is the best concept with submerged storage. The reasons for this are comparable to the reasons why concept 8 was chosen in the evaluation of concepts with floating storage in rigid or flexible tanks. Due to the lack of experience with flexible tanks for use on/under water, rigid tanks will be more reliable. Therefore, concept 4 scored higher on the criteria ‘Reliable storage’, ‘OPEX’ and ‘ESL’. Next to that, rigid tanks will be easier to recycle due to the possibility to use uniform materials. More information on this MCA can be found in table D.8.

Table D.4: MCA of concepts with floating flexible tanks

Criteria	Weights	Concept 5	Concept 6	Concept 7
Safe	0.06	1	3	2
Env. Friendly	0.09	3	1	1
GreenBattery	0.08	2	2	2
ESL	0.18	2	2	3
CAPEX	0.25	4	4	0
OPEX	0.11	2	3	2
Reliable storage	0.10	2	2	2
Solar PV	0.14	2	2	2
Total:	1	2.53	2.58	1.58

Concepts with floating flexible tanks
The results of the MCA for concepts with floating storage in flexible tanks (concepts 5, 6 and 7) can be found in table D.4. Concept 6 scored best on the criteria ‘OPEX’ and ‘Safe’, because the PU is on land, which makes it easier to reach for maintenance and safer to operate. Though, its mooring system that is connected to shore, will not be feasible to use on a lake of more than 20km^2. Concept 7 scores best on the criterion ‘ESL’ due to its mooring system (more information on why this mooring system will be best can be found in section 3.2.3). Therefore, concept 6 in combination with the mooring system of concept 7 is the best concept with floating flexible tanks. More information on this MCA can be found in table D.7.

D.2. Results of the evaluations on requirement level

In this section, the results of the evaluations on requirement level are presented. The results of the evaluation of concepts with submerged, flexible tanks (concepts 1 and 2) can be found in table D.5. The results of the evaluation of concepts with submerged, rigid tanks (concepts 3 and 4) can be found in table D.6. The results of the evaluation of concepts with floating, flexible tanks (concepts 5, 6 and 7) can be found in table D.7. The results of the evaluation of concepts with submerged tanks (concepts 1 and 4) can be found in table D.8. The results of the evaluation of concepts with floating tanks (concepts 6 and 8) can be found in table D.9. The results of the evaluation of concepts with submerged or floating tanks (concepts 4 and 8) can be found in table D.10.

As further explained in chapter 3, for the concepts with floating storage and rigid tanks, concept 8 is the most promising concept.

Table D.5: Evaluation of Concept 1 versus 2 on requirement level

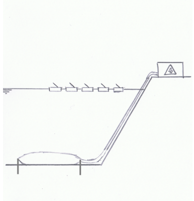
Requirement	Concept 1	Concept 2	Reason
Picture:			
Low risk of drowning	2	0	4: more work on water
Little installation/ maintenance work requiring manpower	1	1	Same kind of concept
Small chance of leakage	1	1	Same kind of concept
Small amount of acid/base in one reservoir	1	1	Same kind of concept
Use of environment friendly materials	1	1	Same kind of concept
Easy volume measurement	1	1	Same kind of concept
Scalability of storage duration	1	1	Same kind of concept
Not decrease efficiency	1	1	Same kind of concept
Resistant against wind speeds (max. 31m/s)	1	1	Same kind of concept
Resistant against waves (max H_{m0} = 1.6m)	1	1	Same kind of concept
Resistant against currents (max 0.94m/s)	1	1	Same kind of concept
Little horizontal space needed for anchoring	1	1	Same kind of concept
Deal with different temperatures (-15C to 40C)	1	1	Same kind of concept
Least deterioration over time	1	1	Same kind of concept
Low component costs	2	0	4: Expensive BFPs
Easy installation	2	1	4: installation of BFP
Good transportability	2	1	4: BFP difficult to transport
Easy maintenance access	1	0	Definition
Little maintenance required	1	1	Same kind of concept
Empty reservoirs easy in motions	1	1	Same kind of concept
Reliable components	1	1	Same kind of concept
Cost effective combination with solar PV	1	1	Same kind of concept

Table D.6: Evaluation of Concept 3 versus 4 on requirement level

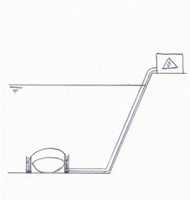
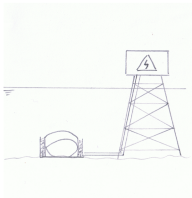
Requirement	**Concept 4**	**Concept 3**	**Reason**
Pictures			
Low risk of drowning	2	0	3: more work on water
Little installation/ maintenance work requiring manpower	1	1	Same kind of concept
Small chance of leakage	1	1	Same kind of concept
Small amount of acid/base in one reservoir	1	1	Same kind of concept
Use of environment friendly materials	1	1	Same kind of concept
Easy volume measurement	1	1	Same kind of concept
Scalability of storage duration	1	1	Same kind of concept
Not decrease efficiency	1	1	Same kind of concept
Resistant against wind speeds (max. 31m/s)	1	1	Same kind of concept
Resistant against waves (max H_{m0} = 1.6m)	1	1	Same kind of concept
Resistant against currents (max 0.94m/s)	1	1	Same kind of concept
Little horizontal space needed for anchoring	1	1	Same kind of concept
Deal with different temperatures (-15C to 40C)	1	1	Same kind of concept
Least deterioration over time	1	1	Same kind of concept
Low component costs	2	0	3: Expensive BFPs
Easy installation	2	1	3: installation of BFP
Good transportability	2	1	3: BFP difficult to transport
Easy maintenance access	1	0	Definition
Little maintenance required	1	1	Same kind of concept
Empty reservoirs easy in motions	1	1	Same kind of concept
Reliable components	1	1	Same kind of concept
Cost effective combination with solar PV	1	1	Same kind of concept

Table D.7: Evaluation of Concept 5 versus 6 versus 7 on requirement level

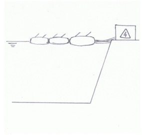
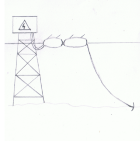
Requirement	**Concept 5**	**Concept 6**	**Concept 7**	**Reason**
Picture				
Low risk of drowning	1	2	1	PU on land safer, than on BFP, than on water
Little installation/ maintenance work requiring manpower on water	1	2	2	On water with manpower
Small chance of leakage	1	0	0	6,7 long pipes, possible failures
Small amount of acid/base in one reservoir	1	1	1	Same reservoirs
Use of environment friendly materials	1	1	1	Rather same materials
Easy volume measurement	0	0	0	All flexible bags
Scalability of storage duration	1	1	1	Same kind of concepts
Not decrease efficiency	2	1	1	6,7 transport losses
Resistant against wind speeds (max. 31m/s)	1	1	1	Same kind of concepts
Resistant against waves (max H_{m0} = 1.6m)	1	1	1	Same kind of concepts
Resistant against currents (max 0.94m/s)	1	1	1	Same kind of concepts
Little horizontal space needed for anchoring	2	0	1	5: best kind of mooring, 6: unfeasible, 7: lot of space needed
Deal with different temperatures (-15C to 40C)	1	1	1	Same kind of concepts
Least deterioration over time	1	1	1	Same kind of concepts
Low component costs	2	2	0	PU on land cheapest, than on water, than on BFP, but pipes
Easy installation	2	1	0	6,7 pipe laying, 7 BFP
Good transportability	2	2	1	BFP requires special transport
Easy maintenance access	1	2	1	On land easier
Little maintenance required	1	1	1	Same kind of concepts
Empty reservoirs easy in motions	1	1	1	Same kind of concepts
Reliable components	1	1	1	Same kind of concepts
Cost effective combination with solar PV	1	1	1	Same kind of concepts

Table D.8: Evaluation of Concept 1 versus 4

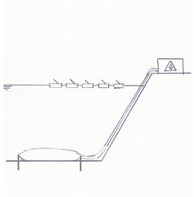
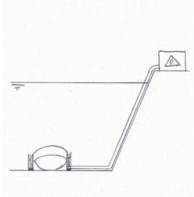
Requirement	Concept 1	Concept 4	Reason
Picture			
Low risk of drowning	1	1	Same kind of concept
Little installation/ maintenance work requiring manpower	1	1	Same kind of concept
Small chance of leakage	1	1	Same kind of concept
Small amount of acid/base in one reservoir	1	1	Same kind of concept
Use of environment friendly materials	0	1	Easier with rigid tanks
Easy volume measurement	0	2	Definition
Scalability of storage duration	1	1	Same kind of concept
Not decrease efficiency	1	1	Same kind of concept
Resistant against wind speeds (max. 31m/s)	1	1	Same kind of concept
Resistant against waves (max H_{m0} = 1.6m)	1	2	Rigid tanks more robust
Resistant against currents (max 0.94m/s)	1	2	Rigid tanks more robust
Little horizontal space needed for anchoring	1	1	Same kind of concept
Deal with different temperatures (-15C to 40C)	1	1	Same kind of concept
Least deterioration over time	1	2	Rigid tanks more robust
Low component costs	2	1	Flexible bags are cheaper
Easy installation	1	1	Same kind of concept
Good transportability	2	0	Flexible bags are easy to transport
Easy maintenance access	1	1	Same kind of concept
Little maintenance required	0	2	Flexible bag is not proven technology
Empty reservoirs easy in motions	1	1	Same kind of concept
Reliable components	0	2	Flexible bag is not proven technology
Cost effective combination with solar PV	1	1	Same kind of concept

Table D.9: Evaluation of Concept 6 versus 8

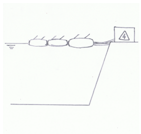
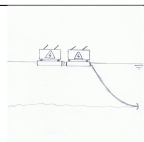
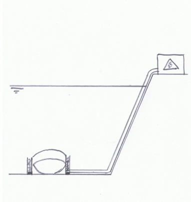
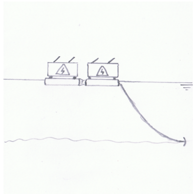
Requirement	**Concept 6**	**Concept 8**	**Reason**
Picture			
Low risk of drowning	2	0	F: Onshore PU possible
Little installation/ maintenance work requiring manpower	1	1	Both floating, will require more or less same procedure
Small chance of leakage	1	2	F: on average more space between tanks and PU, so larger chance of leakage
Small amount of acid/base in one reservoir	0	2	Reservoirs can be of same size
Use of environment friendly materials	1	2	F: Tank vaak van een of ander weefsel
Easy volume measurement	0	2	Bij flexible tank lastiger te realiseren
Scalability of storage duration	1	1	Both easy to adjust
Not decrease efficiency	1	1	F: Unknown yet Depends on detailed design
Resistant against wind speeds (max. 31m/s)	1	0	R: will be more rough than floating flexible bags
Resistant against waves (max H_{m0} = 1.6m)	0	2	F: less strong material
Resistant against currents (max 0.94m/s)	1	1	Streamlined or robust
Little horizontal space needed for anchoring	1	1	All anchor types possible
Deal with different temperatures (-15C to 40C)	1	1	Equal, because same kind of system
Least deterioration over time	1	1	Supposed to, but not influenced by UV and Marine growth
Low component costs	2	1	Flexible bags cheaper, large part of the costs (zeeland ademt)
Easy installation	1	1	Installation methods comparable, costs too
Good transportability	2	1	Bags can be transported more easily
Easy maintenance access	2	2	All components reachable over water
Little maintenance required	0	2	Bags will require more maintenance, because they are new technology
Empty reservoirs easy in motions	1	0	Bags compress when emptied
Reliable components	0	2	Rigid tanks will be more reliable, because newer
Cost effective combination with solar PV	1	2	Definition

Table D.10: Evaluation of Concept 4 versus 8

Requirement	Concept 2	Concept 8	Reason
Picture			
Low risk of drowning during activities	1	2	Underwater divers needed
Little installation/ maintenance work requiring manpower	2	1	Underwater more machine work
Small chance of leakage	1	2	Underwater more failure points (pipes)
Small amount of acid/base in one reservoir	1	1	Depends on detailed design
Use of environment friendly materials	1	1	Same for both concepts
Easy volume measurement	1	1	Independent of tank location
Scalability of storage duration	1	1	Possible in both cases
Not decrease efficiency	1	1	Floating potentially smaller distance tank-PU
Resistant against wind speeds (max. 31m/s)	2	1	Definition
Resistant against waves (max H_{m0} = 1.6m)	2	1	Definition
Resistant against currents (max 0.94m/s)	1	1	Definition
Little horizontal space needed for anchoring	2	0	Definition
Deal with different temperatures (-15C to 40C)	2	1	Above water more influence of temperature, lack of experience
Least deterioration over time	1	1	Both can deal them
Low component costs	1	1	Independent of tank location
Easy installation	0	2	Divers needed underwater
Good transportability	1	1	Independent of tank location
Easy maintenance access	1	2	Definition
Little maintenance required	1	1	Independent of tank location
Empty reservoirs easy in motions	2	0	Definition
Reliable components	1	1	Independent of tank location
Cost effective combination with solar PV	0	2	Definition