Universiteit Leiden

TU Delft

INDUSTRIAL ECOLOGY MASTER THESIS

Life Cycle Assessment of Offshore Low Head Pumped Hydro Storage.

Mikel Fadul Bonamusa

Under the supervision of:
Bernhard Steubing
Antonio Jarquin Laguna

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Credits picture: https://www.environmentalleader.com/2016/07/while-there-are-obstacles-hydropower-may-spring-to-life-says-a-government-study/

Executive Summary

Aiming to comply with the Paris Agreement, the reduction of Europe's GHG emissions in the energy sector is a must. Due to the intermittency of renewable sources, energy storage technologies are essential to this plan. Offshore Low Head Pumped Hydro Storage (LH PHS) is presented as an alternative to partly solve this problem. Considering that its infrastructure entails a reservoir of a 5km diameter ring in the middle of the sea and needs millions of tonnes of concrete, sand, granite and steel among other materials for its construction; environmental concerns arouse, which this report aims to address.

Information from the Alpheus project about the engineering requirements for an offshore LH PHS plant is used, following ISO 14044 Life Cycle Assessment (LCA) methodology. In this study, the construction, maintenance and operation of an offshore LH PHS plant are assessed, focusing on Global Warming Potential (GWP), Water Use Depletion Potential (WUDP) and Abiotic Depletion Potential for Elements (ADP-E). This is studied with and without the input of electricity, sourcing it from wind or from the Dutch grid mix. Moreover, these results are compared with Lithium iron phosphate (LFP) Batteries and for Wind-Green Hydrogen.

For the construction, operation and maintenance of the LH PHS plant, it is estimated that the emissions would reach 2.8Mt of CO2-eq, 601 million m3 of water and 140.2t of Sb-eq. These emissions are mainly shared between civil and electromechanical infrastructure, the former has more relevance for GWP with almost 56% of the emissions whereas the latter reaches 69% for WUDP and 98% for ADP-E. When electricity is incorporated into the equation and these emissions are translated per kWh, emissions from the generation of electricity exceed 2.4, 5.6 and 1.8 times those emissions from the infrastructure for GWP, WUDP and ADP-E. When comparing LH PHS with other technologies using wind as the only source of electricity production, LFP Batteries outperform LH PHS most of the time for GWP and WUDP, whereas LFP are consistently the worst performer for ADP-E. LH PHS always performs better than Green Hydrogen in all three impact categories.

If emissions reductions are to be achieved in the LH PHS case, the focus should be put on the electricity side: improving the efficiency of the plant, storing only clean energy and improving the performance of renewables. Finally, there are other considerations to LH PHS implementation that should be taken into account that are not assessed in this report. The use of materials and their circularity must be considered, as well as the social ramifications of projects like PHS and mining materials for Li-ion Batteries. Furthermore, impacts on biodiversity must be addressed and its damages should not only be minimized but restored or even improved.

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1 Introduction

In compliance with the Paris Agreement, signing countries committed to limit global warming below 2ºC, preferably 1.5ºC (United Nations, 2015). In Europe, energy accounts for more than 75% of its GHG emissions (CEU. COMMU., 2019). Thus, one of the key points here is to electrify different sectors that currently work with fossil fuels, from cars to energy production.

For this, the European Union came up with a road map to make the EU climate-neutral by 2050. This is the European Green Deal, which has a strong decarbonizing tendency, focusing on the Energy transition to renewables. This is a titanic task that requires significant investment, reaching 2030 goals will require €260billion of additional annual investment and also, more than 25% of the EU's long-term budget ought to be dedicated to climate action (European Commission, 2019). Nonetheless, it would be naive to think that this only answers ecological claims, as we have already reached the peak production for oil (Kerr, 2011; Maggio & Cacciola, 2012) and for gas, uranium and coal are expected to come in the next decades (Kharitonov et al., 2014; Lu et al., 2018; Maggio & Cacciola, 2012). Moreover, fossil fuel prices are increasing at the same time that renewables costs are going down (Kalair et al., 2021). Therefore, the EU is interested in securing affordable energy supply for individuals and businesses (The European Green Deal, 2019).

Although energy generation is essential for the energy transition, it is not enough. Asymmetry between energy production and consumption times rises with the increasing use of intermittent energy production sources like solar and wind (Hoffstaedt et al., 2022). To cope with that, energy storage stands out as the best candidate (Hainsch et al., 2022). Moreover, the scientific community agrees that massive energy storage is a critical technology for renewable electricity production (Rehman et al., 2015). Several technologies have been suggested to do so, including Li-on Batteries, compressed air storage, hydrogen cells, hydropower plants among others (Javed et al., 2020). This last method however is the most mature, currently having more capacity for energy storage than the rest of the alternatives together, as depicted in Figure 1.

PHS is a widely commercially accepted and well-established technology for large-scale energy storage. It functions as a hydropower plant, letting water flow from an upper basin to a lower one, generating electricity in the process and, pumping water upstream when there is an electricity surplus. Nonetheless, traditional hydropower plants rely on high orographic elevation differences to function. This makes hydropower technologies not viable for countries with little or no mountains in their geography, like The Netherlands or Denmark. This is what Low Head Pumped Hydro Storage (LH PHS) aims to tackle. This project aims to study the techno-economic feasibility and advance the technology for a hydropower plant in the sea with a small height difference (20 meters) and relying on large amounts of water, it could store and generate enormous amounts of electricity.

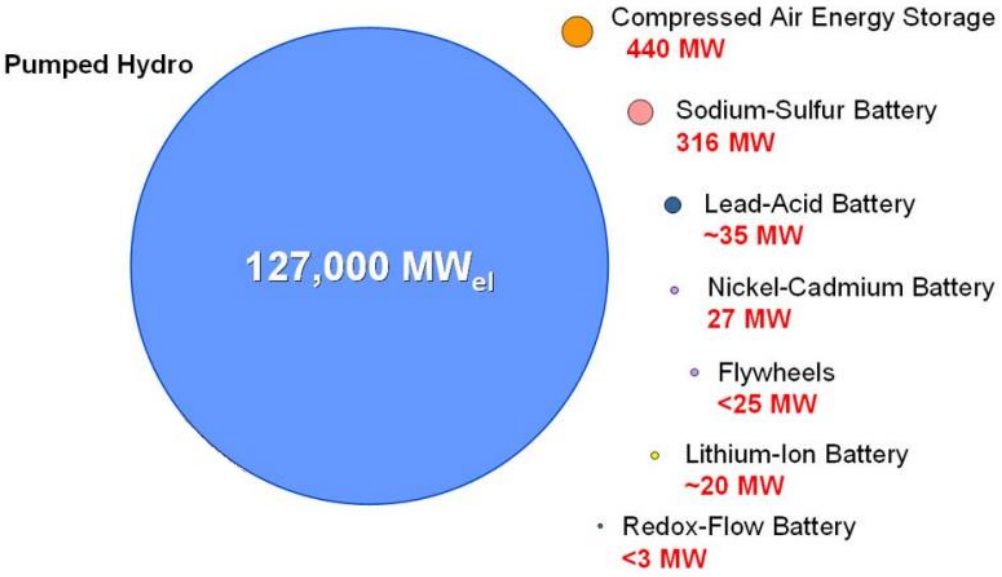


Figure 1. Energy storage capacity globally (Rastler, 2010), in red, the installed capacity of each technology in MW.

In the energy transition we all have to be sure that the alternatives put in place are better than the ones being substituted, and thus the environmental impact of these type of infrastructure is always relevant. However, in this case the environmental performance is especially important due to the large infrastructure that it entails. Life Cycle Assessment (LCA) stands out as a widely accepted methodology to understand the different environmental impacts of products and services, from estimating CO2-eq emissions, to freshwater eutrophication or land use. Therefore, this thesis aims to estimate the environmental footprint of LH PHS technology by studying different scenarios to compare the performance of LH PHS.

1.1 Knowledge Gap and Relevance

In previous studies, it has been assessed the environmental performance of PHS individually (Gemechu & Kumar, 2022; Mahmud et al., 2018; Suwanit & Gheewala, 2011), of other store technologies (Hiremath et al., 2015) and also they have been studied together (Gagnon et al., 2002). However, offshore LH PHS environmental impacts have not been assessed before, being this, the first LCA on LH HPS. The technology used in this study differs from traditional PHS because of its location, but mainly because of it relies in small height differences.

Having the plant offshore means that the whole construction will have to be done through ships, which will have different emissions than trucks, for example. But also means that there will not be biogenic emissions during the operation phase. This fact is important because some authors estimate that up to 90% of the CO2-equivalent (CO2-eq) emissions from PHS technologies could come from the decomposition of organic matter due to flooding the area where this organic matter was (Gemechu & Kumar, 2022).

The second difference takes into account the height difference, which affects the amount of energy that can be produced and therefore, stored. Since the height difference will be much lower than in regular PHS plants, the amount of water needs to be greater. This influences directly the size of the construction, affecting the space needed to occupy, which derives in the destruction of underwater wildlife and the amount of material used.

This knowledge gap is not only interesting per se, but estimating the environmental impact of this project aligns with two European goals: the imperative necessity of massive energy storage and the ecological desire of the EU to reduce emissions to net zero by 2050.

1.2 Goal and Scope

1.2.1 Goal definition and research questions

This report has the goal of providing information about the environmental burdens of offshore Low Head Pumped Hydropower Storage (LH PHS) technology and how this infrastructure performs when comparing it with other storage alternatives. The results of this report aim to be used as a decision-making tool for the further development and definition of the Alpheus project. It is intended to provide useful information to identify hotspots and prioritize different measures for environmental considerations.

This study is conducted by a student of the Industrial Ecology Master's and the commissioner is the Alpheus project. Interested parties are mainly the people of the Alpheus project, other research teams focused on LH PH.

Having this under consideration, one main research question is proposed for this study and three sub-research questions are used to itemize it into more tangible research proposals.

What is the environmental footprint of the construction, operation and maintenance of a Low Head Pumped Hydro Storage plant and how does it compare to that of other energy storage technologies?

- *What are the environmental impacts linked to the construction of the offshore LH PHS?*
- *What are the environmental impacts linked to the storage of electricity in LH PHS?*

- *How does storing electricity with LH PHS compare with other technologies such as LFP batteries and Green Hydrogen?*

1.2.2 Scope definition

The reported LCA aims to cover the major phases of the LH PHS plant. Especially in the construction stage, where both civil and electromechanical infrastructure have been assessed. This is done considering the components that are expected to have a major impact (civil and electromechanical equipment) and leaving out of the scope equipment and machinery that are expected to have a minor role in the environmental footprint or are not estimated yet in the Alpheus project as HVAC and piping systems. This study has a cradle-to-gate approach for all the processes of the LCA with two exceptions: Concrete and sea cables are assessed considering a cradle-to-grave approach because the ecoinvent database provides the processes with cradle-to-grave considerations. This cradle-to-gate approach has been adopted to make feasible the workload for a Master's thesis, which consists of one person working for six months, and because of the lack of data at the End-of-Life (EoL) stage. More details on the coverage are depicted below.

As mentioned earlier, most of the environmental information is sourced at ecoinvent, which is a comprehensive life cycle inventory database that provides data and information on the environmental impacts of various products and processes. It is widely used for conducting LCAs and evaluating the environmental footprints of products, services, and technologies.

1.2.2.1 Temporal coverage

The temporal scope aims to be in present dates (around the 2020s'). The age of data is mostly from the 2000s' onwards with a few exceptions, gas supply for example comes from a data package from ecoinvent dated in the 1990s'.

Moreover, the 100 years of the life of the LH PHS plant are also used for the different comparisons and sensitivity analysis unless mentioned otherwise.

1.2.2.2 Geographical coverage

This study considers two possible spots as the location of the plant, one at 45km and another at 90km from Dutch shores. For this project, the location of 45km is selected, more information on the specifics of this topic is covered in the inventory analysis. However, the results of this study could be applied for any other location, considering that the plant is located 45km away from shore.

On the other hand, processes from ecoinvent can be located all around the globe. Processes from Europe have been prioritized, when possible, but also Global processes have been widely used.

1.2.2.3 Technological coverage

Most of the technologies covered in this report are in the developing stages. An offshore LH PHS plant has not been done before, which means that the technology has not been proven yet. On the other hand, this technology is based on traditional PHS, which is a very mature technology. This mentioned novelty is valid for the turbines and their efficiency (70%), the rest of the project is known to be feasible and it is and has been done before. For example, the civil infrastructure presented in this study is very similar to the approach DEME Group and Jan De Nul have for the construction of an Energy island on the sea close to Belgian shores (DEMEGroup, 2023). Moreover, LFP Batteries and Green Hydrogen technologies have been around for years. However, they are also still to be proven in the scales mentioned in this project.

1.2.2.4 Environmental scope

As mentioned in the goal section, the purpose of this report is to complement the techno-economic analysis of the Alpheus project, which is a European H2020 research project. For this reason, this report tries to follow European recommendations and guidelines. Thus, besides following ISO 14040, EU recommendations on LCA have also been followed in terms of category indicators (a detailed explanation of this is provided in the Impact assessment section). Nonetheless from these indicators, only Global Warming Potential, Water Use Deprivation Potential and Abiotic Depletion Potential (for elements) have been thoroughly assessed. Additionally, a comprehensive Bill of Material (BOM) is included for the alternatives to thoroughly consider and evaluate material scarcity. On the other hand, the rest of the indicators are presented for transparency purposes and to provide a wider picture of the environmental impacts of the alternatives assessed; these can be found in Annex 1.

Moreover, it is relevant to mention that, differently than in traditional PHS plants where biogenic CO2-equivalent (CO2-eq) emissions play an important role (Gemechu & Kumar, 2022), since the plant assessed in this study is placed in the North Sea, these emissions are not assessed due to two factors. First, these biogenic emissions are based on the release of carbon due to the decomposition of vegetation because of flooding the area and due to the release of sedimented organic carbon after the decommissioning stage. Both things do not occur in this project. Second and most important, due to the novelty of this project, to the knowledge of the author there is a lack of information in public literature about biogenic emissions in off-shore LH PHS. It is expected that there is a destruction of life in the seabed that produces emissions, however, it is uncertain how much vegetation and other types of life lay in that area, which makes it challenging to estimate their impact, both for CO2-eq emissions and for biodiversity loss.

It is important to mention, because the plant studies are placed in the North Sea, that the emissions studied in this report do not consider environmental damages derived from the erosion of the sea to the machinery or other infrastructure nor the location of the plant. The LCA methodology applied focuses on the emissions from the raw material production and works necessary for the construction, operation and maintenance of the electromechanical equipment and civil structure (as detailed in the inventory analysis). This is of special relevance for those impact categories involving the marine ecosystem (in Annex 1), as these categories estimate the damages produced in the supply chain, not during the lifetime of the LH PHS plant.

Similarly, when mentioning land use, this impact category focuses on the land used to produce the materials for the construction and maintenance of the site. In any case considers the land occupied by the site itself, which, furthermore, is offshore and not in land.

Finally, maybe the most important indicator is not assessed in this report, biodiversity. Due to its complexity, lack of knowledge of the author of this report and the little data on this topic. All these facts made it unfeasible to address this issue and, at the same time, also consider the rest of the impact categories presented.

1.3 Function, FU, alternatives, reference flow

Defining the function, the functional unit (FU), alternatives and reference flow is the basis of any LCA. In this LCA:

The **Function** is defined as the generation of electricity after the process of charging, storing and discharging.

The Functional unit (FU) is the generation of **1kWh of electricity** after the process of charging, storing and discharging daily for a period of time of 100 years.

The **Alternatives** taken into consideration are the

- LH PHS technology,
- Lithium-ion (Li-ion) batteries type LFP and
- green hydrogen.

However, this study focuses on modelling LH PHS technology due to the goal of this report. However, simpler models (defined as proxies from now on) are used to model LFP Li-ion batteries and green hydrogen as a way to store electricity. More details on these alternatives are provided in the inventory analysis. Furthermore, through scenario analysis, models with and without electricity inputs are produced for each alternative, taking as extreme cases of sourcing electricity with the cleanest and dirtiest electricity production method, which is wind power and The Netherlands' electricity mix from 2021, respectively. This assumption is made because from now on, the grid mix is supposed to provide only cleaner electricity.

The **Reference flows** are, therefore,

- The generation of 1kWh of electricity after storing it daily for a period of time of 100 years with **LH PHS** technology with scenarios providing the cleanest, dirtiest and no electricity.
- The generation of 1kWh of electricity after storing it daily for a period of time of 100 years with **LFP Li-ion** technology with scenarios providing the cleanest, dirtiest and no electricity.
- The generation of 1kWh of electricity after storing it daily for a period of time of 100 years with **Green Hydrogen** technology with scenarios providing the cleanest, dirtiest and no electricity.

2 Methods

In this section, the methodology is explained dividing it into two parts. First, the LCA methodology is explained in itself and its different subchapters.

2.1 Life Cycle Assessment

Since this study is an LCA, the standard from ISO 14040 (2006) was followed. This standard, depicted in Figure 2, divides LCA studies into four steps: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation. These steps are followed in that same order although after finishing certain parts previous steps were revisited, reframed, corrected or expanded.

The Goal and Scope definition is not formally defined in ISO, LCA Handbook from Guinée (2002) is followed. First, the goal of the LCA is described, the intended use of the results discussed, the commissioner of the study is disclosed and the targeted audience of the report is mentioned. Then, the scope establishes the main characteristics of the LCA, which cover temporal, geographical, technological and environmental considerations. Also, the mode of the employed analysis and the level of sophistication of the study are mentioned.

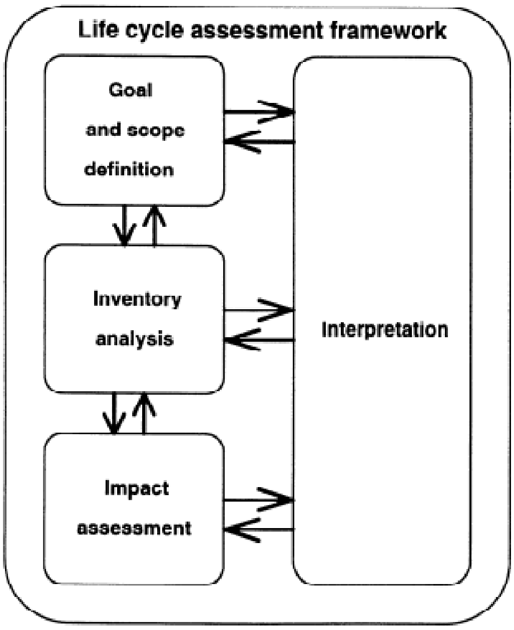


Figure 2. LCA Methodology steps. (ISO, 2006).

The second step is the Inventory analysis. This step entails defining the products systems (in this case the LH PHS plant and its technological alternatives), setting the system boundaries, designing the flowchart of the systems, collecting data for each process, performing allocation and multifunctional considerations if required, building the software model and completing the calculations. The aimed result of this is an inventory table with the environmental inputs and outputs associated with the functional unit for the different impact categories selected.

The Impact Assessment is the step when the results from the inventory analysis are studied and interpreted in terms of environmental footprint and preferences for society. Here, a tailored list of suitable impact categories is defined and selected for the project. The final model results are calculated and grouped by category indicators.

Finally, the Interpretation step analyses the coherence and robustness of the results and concludes. This is done through consistency, completeness, contribution and sensitivity analysis; ending with an analysis from a higher view of the results with a discussion, recommendation and conclusion sections.

2.2 Data gathering

To go on with the LCA modelling, information is needed. First, it is important to get familiarized with the LH PHS project. For that, the first thing that was done was to get in touch with people working on the Alpheus project, which is a project developing the technical details of an offshore LH PHS plant. This was done to know how was the civil infrastructure was thought to be built and what the electromechanical needs would be, *a priori*, most impactful.

In parallel to these conversations, literature about PHS projects and LCA on PHS to get to know where the important details were, which assumptions could be made or not, what did apply to LH PHS from them and what did not. This was done for the three main stages of the lifetime of a product: Production; Use phase and; End-of-Life. These stages are translated into Construction; Operation and Maintenance and; Decommissioning. The results of this literature review can be found in the different stages described in the Inventory Analysis. Furthermore, other technologies that were compared with LH PHS were researched to be able to provide the fairest comparison with the time restraints this project has. For this, Li-ion batteries type LFP and Green Hydrogen were researched.

2.2.1 Interviews

Technical interviews were conducted with people responsible for the civil infrastructure and electromechanical equipment for the Alpheus project.

From the beginning, it was thought that the civil infrastructure would be the hotspot of this project, and therefore much more time and detail were taken into consideration than for the electromechanical part. Much specific information from the Alpheus project has been taken into consideration for this study. More specifically, the alternatives of the construction and which type was finally chosen for this study (Figure 3), the dimensions of the plant and the specific measures of the different parts (Foundations, Caissons, inner berm and protection layer), the parts of this construction type and the construction sequence with the needed ships to carry on with this task. Finally, assumptions made for the development of this study were consulted with the experts to confirm them, an example of this is the type of geotextile used for the protection layer used in the LCA model or the type of cement used (lightweight or not).

For the electromechanical part, the focus was put in the beginning on the turbines, which was the information easily available from the Alpheus project. Their number and the types and amount of materials per turbine were facilitated, which allowed to model their composition in the LCA. The rest of the electromechanical equipment is modelled based on existing literature (ABB, 2003; Alsaleh & Sattler, 2019; Gemechu & Kumar, 2022; Molina Gómez et al., 2022; Schmidt, 2006; Schreiber et al., 2019).

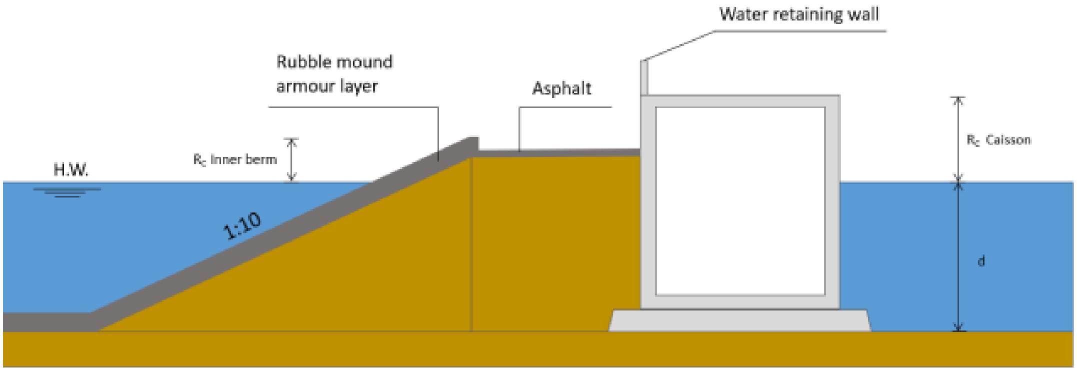


Figure 3. Cross-section of the dam, with its different parts.

2.3 Inventory analysis

2.3.1 System boundaries

2.3.1.1 Economy-Environment system boundary

Each economic flow is followed downstream until the product needed from the different alternatives is obtained. At the same time, economic flows are followed upstream until they become environmental flows (considered in ecoinvent).

Thus, the model built for this project considers the economic and environmental flows resulting from the construction, maintenance and operation of the LH PHS, except for the waste produced. For the Li-ion batteries model, only the electricity and the batteries themselves have been considered, whereas for the Green Hydrogen model only electricity inputs (from wind energy) have been taken into account. More information on these processes can be found in the sections below.

2.3.1.2 Cut-offs

Important to highlight is the fact that waste resulting from the construction of the plant and the whole decommissioning stage are not considered in this study. This decision is made due to the difficulty of assessing these sections properly in the time available; and because it is assumed that the impacts derived from these stages are not decisive for a clear picture of the environmental burdens the project entails.

2.3.2 Flowcharts

Flowcharts depict how the LCA has been modelled in Activity Browser (AB). Due to the size and complexity of the LH PHS chart, it seems appropriate to show first a simplification of the model, depicted in Figure 4. However, the flowcharts of specific stages can be found at the end of the description of each stage and, the complete version of the LH PHS flowchart can be found at the end of the description of the alternative.

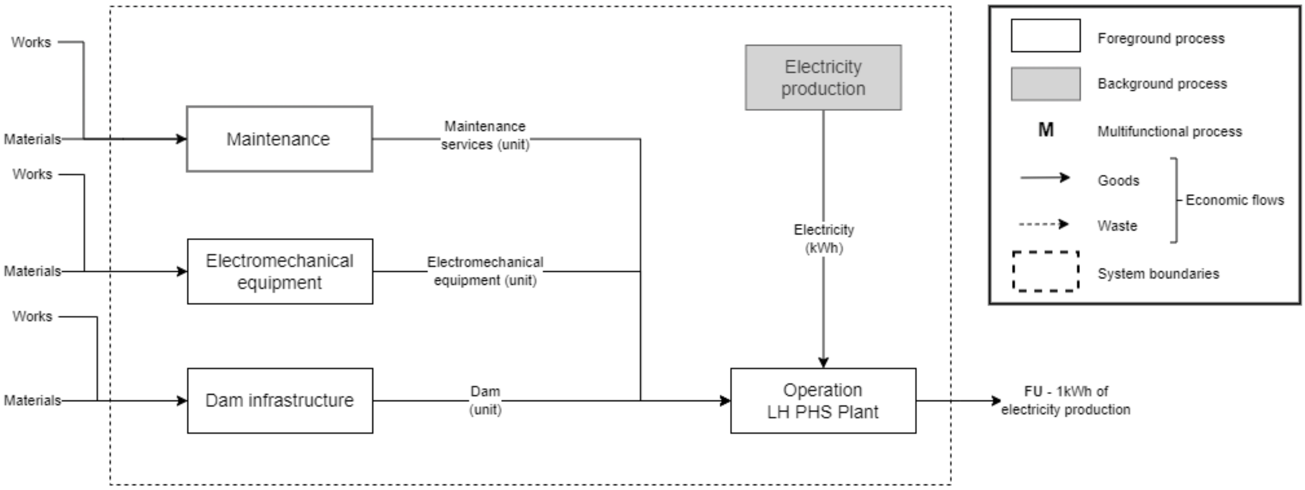


Figure 4. Simplified Flowchart of the whole LH PHS project.

2.3.3 LH PHS Infrastructure construction

This project started with the basics compiled by Gemechu and Kumar (2022) and their literature review about the environmental impacts derived from hydropower energy and the details to take into account when building an LCA for this type of plant. From literature review, GHG emissions are at the centre of the reflection and analysis and thus, the focus is put on this impact category.

The construction stage is based on the energy and material requirements for the extraction of resources, their transportation, component manufacturing and finally dam construction. GHG emissions from this stage are directly correlated with the size of the plant since that will determine the amount of material and work needed for its construction. However, other facts like construction techniques, soil conditions and hydrologic characteristics will influence the energy requirements of this stage. Emissions are mainly produced due to the consumption of fuel and electricity by the equipment needed in the different stages of construction (Gemechu & Kumar, 2022).

It was known from the beginning that the materials in this part of the project were not novel or unconventional like composites or very specific metal alloys, but rather the opposite: Steel, concrete, sand and rocks. However, the specific type of each material was important to find out, since it is important to be precise and even more in a special environment like the marine one, where erosion is more aggressive than in land. All the details of the data selection can be found in the inventory analysis.

For this section, the relevant parts to know are that the emissions from shipping and granite production are sourced from literature and not from ecoinvent. Moreover, from the electromechanical equipment; transformers, subsea cables and electronics estimations are based on literature (ABB, 2003; Alsaleh & Sattler, 2019; Gemechu & Kumar, 2022; Molina Gómez et al., 2022; Schmidt, 2006; Schreiber et al., 2019), but proxies from ecoinvent were used in the LCA model.

The geographical location of the plant had two possible locations (see Figures 5 and 6) (DELFT UNIVERSITY OF TECHNOLOGY, n.d.). Between these two alternatives, Site 02, the closest to the shore is selected.

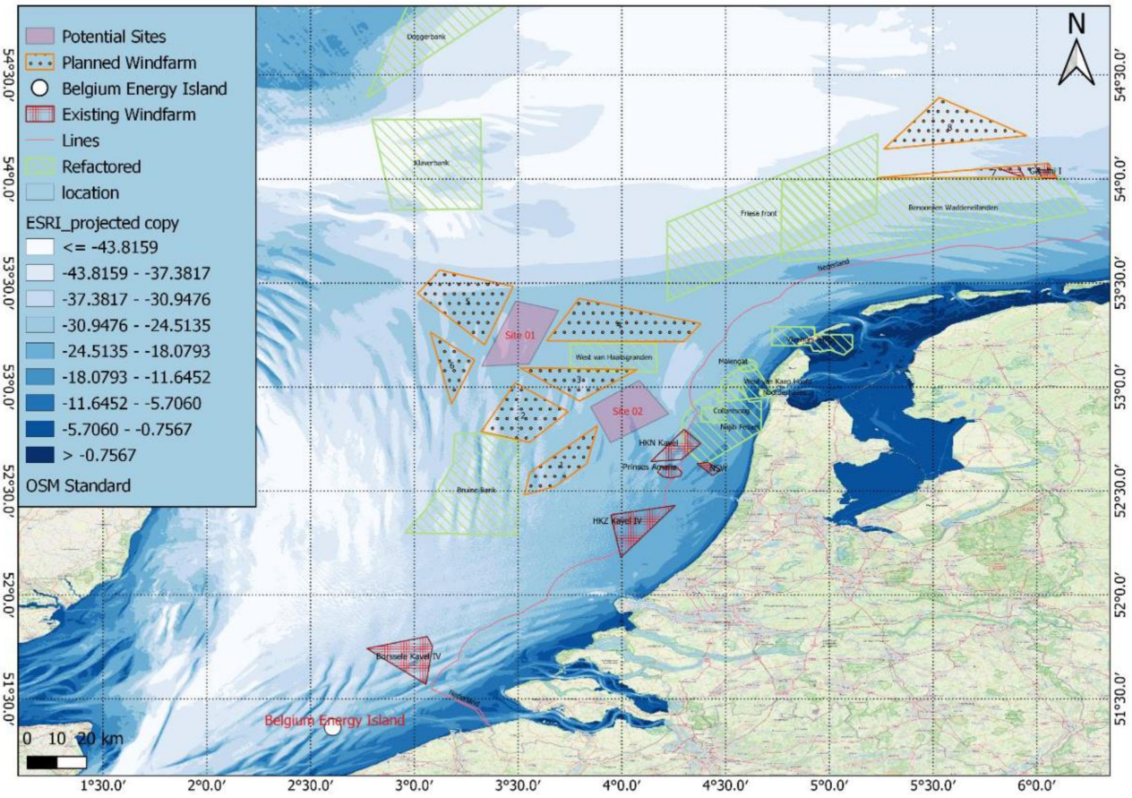


Figure 5. The geographic location of the study, based on the Alpheus project.

Below the description of the construction, maintenance and operation stages are described and the flowchart of each section is shown. Not only are they described, but all considerations for the model and assumptions taken into account are captured in the following sections.

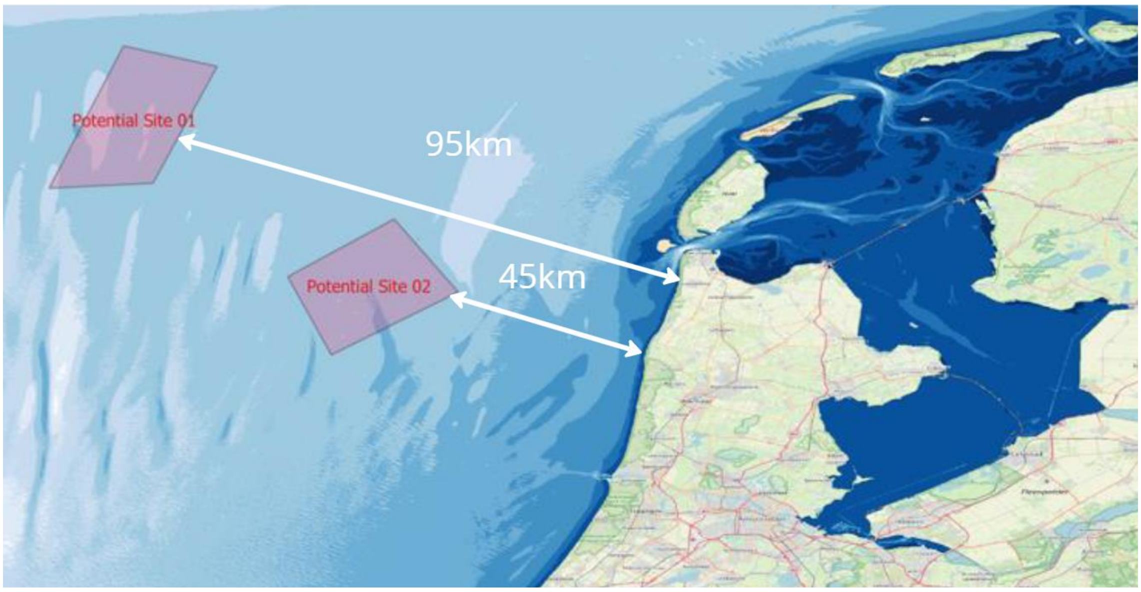


Figure 6. Distance from the two possible sites to place the LH PHS plant from the Dutch shores.

2.3.3.1 Civil infrastructure

The civil infrastructure refers to the non-moving parts of the construction, i.e. The dam. The Alpheus project had different alternatives for the design of the ring dam, however, only the most advanced with information about the structure was selected to develop its environmental footprint. This alternative is the Caisson design, which is based on building a circular wall with big rectangular blocks made out of reinforced concrete forming this wall. To make the study feasible, the basic elements that constitute the most relevant parts of the dam are considered. These elements are the foundations, the Caissons, the inner berm and the protecting layer. In this stage, the material and work needed for the construction are considered. In this study, the dam is shaped in a circle with a diameter of 5km, Figure 7 shows a plan and section view where the caisson and inner berm are identified.

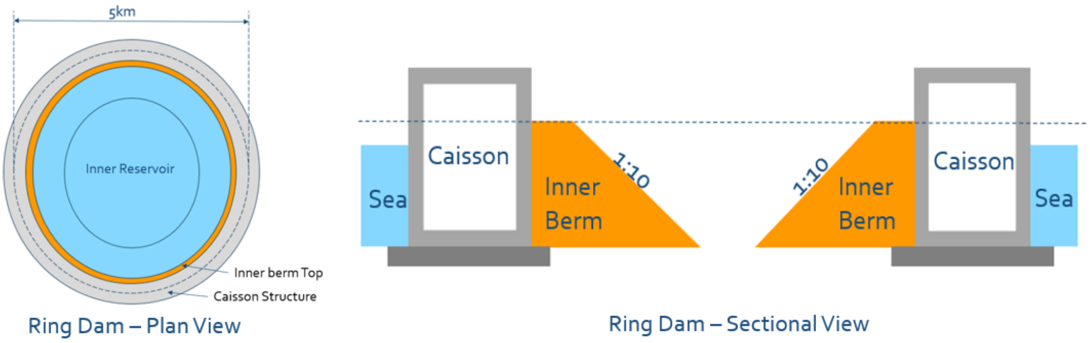


Figure 7. Simplified top and cross-section of the dam.

Next, each of the four major parts of the dam is defined and their material and work needs are explained and estimated together with the assumptions considered.

Since this plant is planned to be built in the sea, the only way to get machinery and materials there is through ship transport. Moreover, depending on the different activities needed, different ships have to be used and, therefore, modelled. All this variety of ships is not present in ecoinvent, so to get the environmental burdens the emissions from the fuel are inserted in the database following Arvesen et al. (2013) supplementary information (Table S6). Here, the emissions for Marine Gas Oil (MGO) and Heavy Fuel Oil (HFO) are accounted for. This information however is stated in grams of fuel per MJ of output, which means that the future calculations must be entered as energy outputs.

To estimate the consumption of the ships, a simple calculation following Cuyper et al. (2014) reasoning is used; where FC is Fuel consumption, sfc is specific fuel consumption, t is time and P is power.

$$FC = sfc \cdot t \cdot P$$

Equation 1

Assumptions had to be made to make this work. Based on the studies calculations from Cuyper et al. (2014), Arvesen et al. (2013) and Cooper & Gustafsson (2004), the sfc value assumed to be 190g/kWh. In this last study 190g/kWh matches when the ships used diesel engines going in a slow speed regime, which matches Arvesen et al. (2013) assumptions of an average load carried of 30% and the study of Cuyper et al. (2014) when the engine load is around 50%.

To estimate the time of use, and following Arvesen et al. (2013) assumptions, 30% of the maximum speed of the different ships have been used to travel the distance needed, these variables change depending on the type of tasks and ship. This means that time will depend on the speed of the ship and the distance of the trip, which will depend on the stage of construction. Similarly, the power of the ship is taken from the specifications of the fleet from Boskalis or Van Oord shown in their webpage (*Equipment | Van Oord/*, 2023; *Fleet and Equipment | Boskalis*, 2023), which again, will vary depending on the ship. All the ship calculations can be found under each specific task in Annex 2.

However, as mentioned before, MGO and HFO needs have to be input in energy needs and have to take into account the tonnes-kilometre (tkm) from the ship transports. For this reason, fuel consumption is divided by one individual trip size (in tkm) to have the fuel consumption per tkm of each ship. This trip size will depend on the specific task the ship is doing. After this, it is divided by the specific fuel consumption of the ship to get the result in energy output, this provides energy needs per tkm, which makes it very easy to estimate the emissions since the only input required is the total trip size, considering the total material needs of the project.

The ship calculations are made considering the weight of the ship and the weight of the cargo. It is assumed that the ship has to make the trip twice, one with cargo and one empty. The total trip size (in tkm) is the result of Equation 2, where SW is the Ship weight, C is the cargo weight and d is distance.

$$Total\ trip\ size = d \cdot (SW + C) + d \cdot SW$$

Equation 2

An assumption is made where the weight of the ship is 0.1 times the weight of the cargo, and thus, the equation turns in:

$$Total\ trip\ size = d \cdot (1.2 \cdot C)$$

Equation 3

Thus, each trip size has been estimated with a coefficient of 1.2 to consider the trip the ship does without cargo.

All these considerations are focused on in the construction stage due to special ship uses. However, processes like 'Steel production' have been modelled from a 'market' perspective, which already includes transport.

Finally, the shipping industry is also expected to change in the following 100 years to reduce its emissions. This fact approaches taken to be most likely conservative in terms of emissions, overestimating the ship needs of the future ship works as Maintenance works. The flowchart of this section is shown at the end of the section in Figure 9.

2.3.3.1.1 Foundations

The foundations are part of the infrastructure that will hold the structure placed above the sea. It is the part in any building that is placed first and holds the weight of the structure in its position. The full calculation report is reported in Annex 2, in this section it will be only mentioned that the overall section is divided into four parts to ease the calculations.

On the other hand, it is considered that the material used for this foundation is granite. The problem with granite is that there is no information in ecoinvent and thus, data from Braga et al. (2017) is used to estimate the environmental burdens of this material. In this report, it is assumed that these rocks will come from the South of Norway, from a quarry in Rekefjord. All the needs for the construction are vessels that deposit the rocks on the seabed.

It is estimated that the total volume of the foundation is 3.86e6 m3. Considering a density of 3.13 ton/m3 (RSA, 2021), a total weight of 1.21e7 tons are estimated necessary. First, these rocks have to be transported from a quarry in the south of Norway with Bulk transporters to the port of Rotterdam. The distance between these two sites is 720km, which means that the total travel size is 8.73e9 tkm.

From the Port, Fallpipe and Sidestone Dumping vessels are used to move the rocks to the construction site, 100km away from each other. Depending on the section of the foundations a Fallpipe vessel or a Sidestone vessel are used. In summary, it is assumed that the Dumping vessel will place section C' (see Annex 2 for more information) whereas the Fallpipe vessel will be employed for the rest of the sections. Translating this into numbers means that 3.21e6 tons of rocks are deployed by a Dumping vessel whereas 8.91e6 tons are placed with Fallpipe vessels. Thus, the total trip size for the Dumping vessel is 3.21e8 tons whilst for the Fallpipe is 8.91e8 tons. These calculations have been done considering the characteristics of the fall pipe vessels from Boskalis, Seahorse and Rockpiper; whilst the sidestone characteristics are from the vessel HAM 602 from Van Oord (*Equipment | Van Oord/*, 2023; *Fleet and Equipment | Boskalis*, 2023).

Finally, the foundations are assumed to not require maintenance for the 100 years that the infrastructure will be there.

2.3.3.1.2 Caisson

Caissons are blocks of hollow reinforced concrete with enormous dimensions. In this case, the dimensions are 65.1m long, 22m wide and 35m tall. The volume of the concrete per caisson is 4,360m3 and steel volume is 2% of this (87.2 m3). The remaining empty volume of the hollow part of the block is 45,767m3 and is to be filled with sand.

Knowing this it is estimated that, for a circumference of 5km of diameter, it is needed 241.3 caissons, for the calculations it has been rounded to 242. The joints attaching these 242 caissons are not considered. Thus, the total material needs are 1,055,120m3 of concrete, 21,101m3 of steel and 12,183,175m3 of sand.

When selecting these processes from ecoinvent, the energy needed for the manufacturing of the caissons is neglected assuming that is a small portion of the energy needed for the manufacturing of concrete and steel. To select the specific concrete type, specifications for marine concrete structures (P. E. Smith, 2016) have been followed. Several types of cement match the requirements, type IIIA and type IIB-V with concrete strength of 40 or 50MPa. When assessing these materials in AB, it is seen that the most pollutant (considering GHG emissions) type is IIB-V with 50MPa of strength. This type is the chosen one for the simulation since it is the most conservative approach. On the other hand, the steel chosen for the simulation is reinforcing steel production as it is the one needed for reinforcing concrete production.

It is assumed that the production of the caissons will happen at the Port of Rotterdam, 100km away from the possible construction site. After the construction they are transported to the construction site, 100km away from the Port of Rotterdam, placed in its right position (assumption of 1km of travel) and filled with sand rainbowed from a dredger vessel. The transport is expected to happen with semi-submersible vessels with the capacity of transporting 4 caissons at the same time, while the positioning is assumed to happen with two anchor handling tugs per caisson. The weight of each caisson (without sand) is 11,118 tons, and thus, the total trip size is 1,111,800tkm from the Port of Rotterdam and 22,236tkm for the placement. Finally, 12,183,175m3 of sand have to be rainbowed from a dredger vessel into each caisson. A detailed description of the calculations for dredging activities can be found in the inner berm explanation.

These calculations have been done considering the characteristics of the semi-submersible vessels, White Marlin and Blue Marlin; the anchor handling tugs characteristics are from the vessel Sentosa; and the dredger vessels are from the Queen of the Netherlands and Fairway, all these vessels are from Boskalis. Finally, no maintenance is considered for the caissons.

2.3.3.1.3 Inner berm

The inner berm refers to the sand counterweight that aims to prevent the caissons from moving as a result of wave and current forces. The enormous amount of sand needed for this purpose is expected to be taken from the inside of the future reservoir, making the seabed deeper by 3 meters. The inner berm volume is estimated with the measurements shown in Figure 8. The green rectangle and triangle are the basic shapes in which the berm is divided, with a total of 42,722,769m3 of sand. However, due to the nature of working with sand in the sea, it is expected that major losses will happen, for this reason, three safety coefficients are assigned for spillage, and damage during construction and settlement, with values of 10%, 50% and 10% respectively. The first two coefficients are used to estimate the amount of sand used during the construction, whilst the last one is used for maintenance estimations. This results in a total sand need of 68,356,431m3 for the construction of the berm, with an additional 4,272,277m3 of sand for maintenance.

All this sand, as mentioned before is dredged on-site, which means that there is no need of producing sand onshore and transport it to the construction site. Instead, trailing suction hopper dredgers will suck sand from the seabed, store it in the ship and pump it out in a controlled manner through a pipe system or rainbowed from the ship. This means the dredger activities are composed of three tasks, sucking the sand from the seabed, transporting it to the construction site and pumping it out. For the transport, an average of 1km has been used for the calculations (explained in previous sections). For the dredging and pumping out activities, however, speed has been substituted with dredging and pumping rates (tons/hour). This data was not available in the specifications from the Boskalis vessels, so assumptions of 7,000t/h for dredging and 12,000t/h for pumping out have been made from the ship's power. This concludes in a total trip size of 54,084tkm and energy use of 58,411 MJ/trip for each activity of dredging and pumping out. The same numbers work for the construction and the maintenance, although the number of trips will, of course, change.

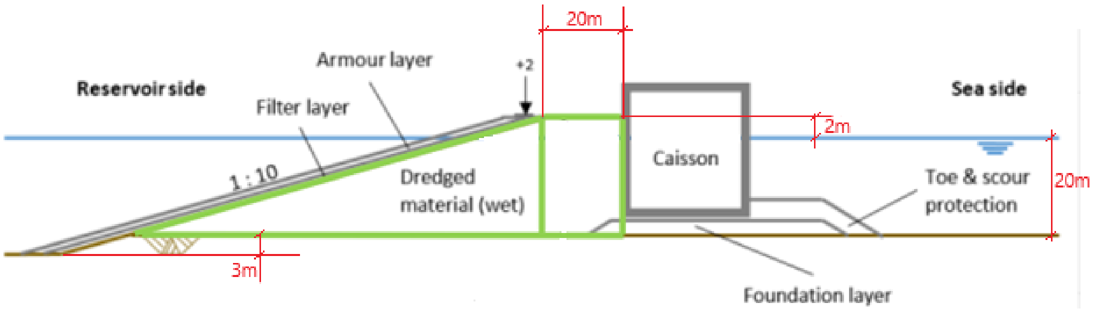


Figure 8. Scheme of the division of the inner berm for its calculation.

2.3.3.1.4 Protecting layer

To keep the sand from the inner berm from excessive spilling a double layer of protection is needed. First, a filter layer, composed of geotextile and second, an armour layer, made from granite rocks.

The geotextile is selected based on the type and use that is expected to be given and, following indications from a leading company in this market (Tencate), their product Polyfelt F is selected (Tencate, 2019). Considering the slope of the inner berm and the flat surface next to the caisson (see Figure 8), the total area to cover is 4,013,841m2, which considering the density of the Polyfelt F translates into 3,411,765kg (the detailed calculations can be found in Annex 2). For that same area but considering a width of 1 meter, there is a need for 12,563,323 tons of granite rock. When modelling this in AB, the granite has been done the same way as it is explained in the Foundations section. On the other hand, ecoinvent 3.9 has a process called "textile, non-woven, polypropylene", which has been used as a proxy for the Polyfelt F (which is mainly composed of polypropylene). At the same time, it has been assumed that the production of the geotextile is done in Europe and since the market processes in ecoinvent are based in India processes, the transport is considered separately. The distance has been based on the factories Tencate has in Europe, the three factories Tencate has in Europe (Austria, Netherlands and France)(*EMEA Head Offices - TenCate Geosynthetics*, n.d.), the French factory has been chosen because it is the one that is not the closest neither the furthest. With a distance of 470km from the French factory to the Port of Rotterdam via highway, this translates into a total trip size of 1,603,530tkm done by lorry.

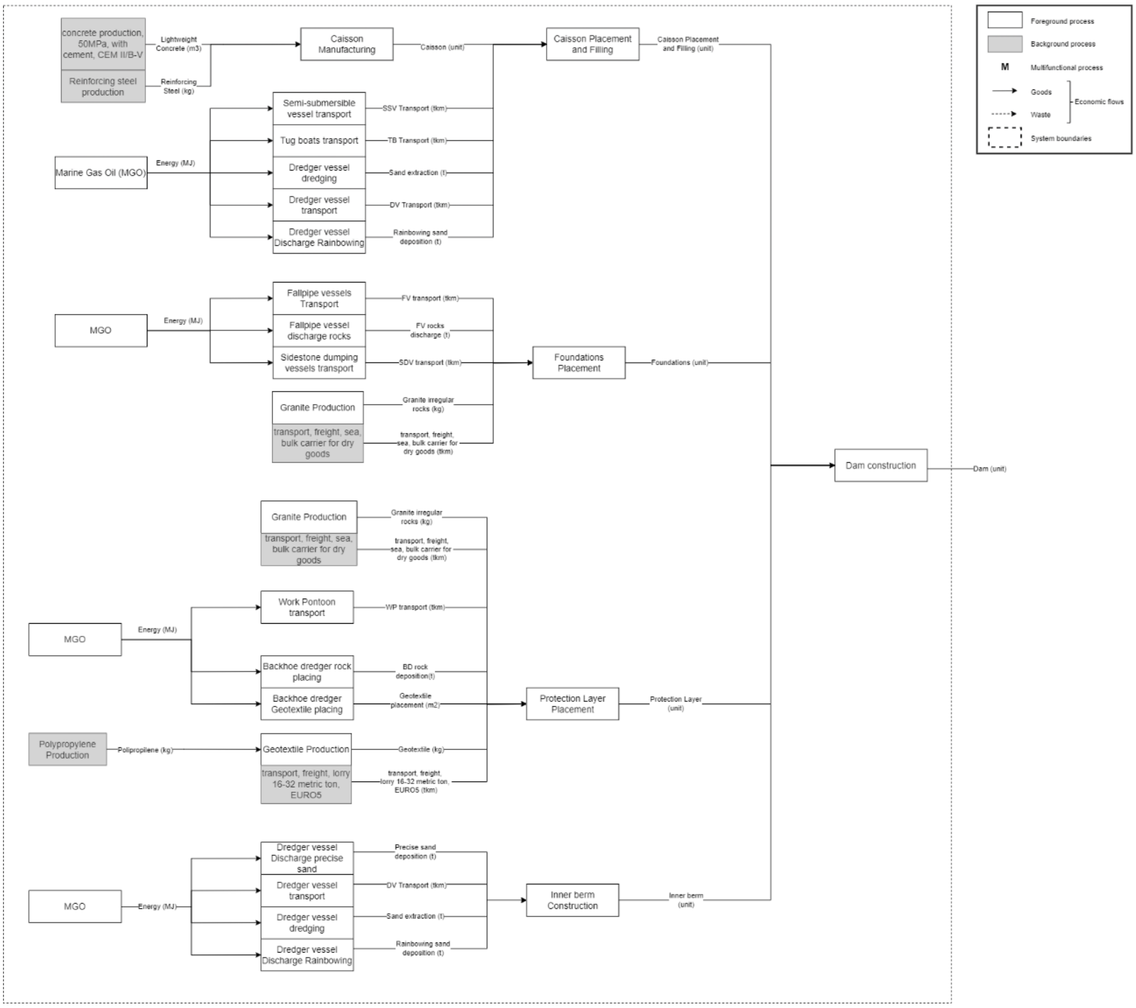


Figure 9. Flowchart of the Dam construction for the LH PHS alternative.

The work for the protective layer is, like the previous phases assumed that will be done through ships. The transport of rocks follows similar steps as the ones described in the Foundations section, first, the rocks are transported a distance of 720km from the South of Norway to the Port of Rotterdam with a bulk carrier, which has been modelled with a process from ecoinvent 'transport, freight, sea, bulk carrier for dry goods' with a total size trip of 9,045,593,146tkm. Then, these rocks and the geotextile are transported in a Work

Pontoon, going from the Port of Rotterdam to the construction site, at 100km of distance. This translates into a total trip size of 1,256,673,558tkm. Finally, all this material has to be placed, a Backhoe dredger is used as a proxy of the type of machinery that would be used. The rationale behind this is to use this vessel to download the material from the ship to its place on the construction site. This is very easy to visualize for the rocks, however, for the geotextile it is assumed that after leaving the rolls of fabric on top of the inner berm, the same machinery will be used for unrolling the fabric. Different times have been assumed for placing the geotextile and the rocks (more information can be found in Annex 2). This resumes an energy consumption of 10.83MJ per ton of rocks and 0.48MJ per m2 of fabric, which translates into overall energy consumption of 135,998,393MJ and 1,926,644MJ respectively. The machinery used for these tasks are BD3 (work pontoon) and MP27 (Backhoe dredger) from Boskalis).

This section of the dam is considered to have 1% of the initial material as maintenance over the lifetime of the plant. Thus, 1% of the rocks and the machinery needed for their transport and placement are estimated.

2.3.3.2 Electromechanical equipment

Electromechanical equipment refers to all the machinery and elements that, as its names pictures, relate to electric or mechanical equipment. This is another way of considering all the equipment that is not taken into account in the civil infrastructure of the dam. This, of course, entails a long list of elements and equipment, from cooling services to subsea cables. Due to the size of this list, a cut-off was made intended to cover the most important elements and the most feasible ones to get data from. Thus, the equipment considered were, turbines, electronics, transformers and subsea cables. The emissions from this equipment will mostly come from the materials and energy used to produce it (Gemechu & Kumar, 2022), and therefore, other phases of the process like the placement of the technology or the End-of-Life are not considered. The flowchart of this section is shown at the end of the section in Figure 12.

2.3.3.2.1 Turbines

The turbines are a key element in the infrastructure, if not the most important, since their job is to pump water when there is an excess of electricity and to produce electricity when there is a demand for it. Moreover, the most important aspects of the plant are directly the result of the technical characteristics of the turbines, such as the roundtrip efficiency or the power capacity, which are 70% and 10MW respectively per turbine. The number of turbines is also important, as it will determine the amount of materials that are needed, but also the total power of the plant. In this project it is projected to use 200 units, reaching a total power capacity of 2000MW. Turbines are composed of different elements and parts that are not detailed in this report, instead bulk amount of material is accounted for. This has implications as different components will have different production methods and treatments that will affect differently to the energy needs, material efficiency and overall, environmental performance. Therefore, the material needs per turbine are shown in Table 1. This approach focuses on the manufacturing phase and leaves out the building, use, transport and dismantling phases. This is done following the findings reported by Padley et al. (2012), which mention that the impacts of these stages are negligible when compared with the manufacturing phase.

Table 1. Type and quantity of materials used per each 10MW turbine.

Material type	Quantity	Unit
Electrical steel	14158	kg
Copper	14158	kg
Stainless-Steel	196340	kg
Steel	39443	kg
Magnet	693.96	kg

The name of these materials is not the same as the ones in ecoinvent, so an approximation has been made, choosing the market process to also consider the transport (Table 2).

Besides the material needs, it is required energy input to manufacture the turbine Literature has been used for gathering this data, more specifically, Schreiber et al. (2019) and the ecoinvent database (offshore turbines) have been used. To extrapolate their data to the needs of this project, the energy needs have been divided by the power of the turbine assessed. This allows them to multiply their average by the power of the turbines needed for the project. This resumes in 50.12kWh/kW (Schreiber et al., 2019) and 33.75kWh/kW from ecoinvent. Making an average concludes in 41.9kWh/kW and, having turbines of 10MW, this translates to 419.35MWh of energy needed for the production of each turbine.

Table 2. Cross-reference between the original material used in the turbines and the material used for the model in AB coming from the Ecoinvent database.

Original material	Ecoinvent process
Electrical steel	Market for low-alloyed steel
Copper	Market for copper concentrated, sulphide ore
Stainless Steel	Market for chromium steel 18/8
Steel	Market for unalloyed steel
Magnet	Market for permanent magnet, for electric motor

2.3.3.2.2 Electronics

Electronics are an important part of any electromechanical equipment since it allows to control and surveillance of the critical parts and parameters of the machinery. Turbines are not an exception, and therefore, electronics are needed for their proper operation. Literature has been used to estimate the amount of electronics needed. However, the power of the assessed turbines in these papers is not the same as the ones assesses in this study. The available information only reports the weight of the electronics used and the weight of the nacelle of the assessed wind turbine. The approach for this part of the electro-machinery has been to estimate the percentage of electronics plays in the overall weight of the nacelle and then extrapolate this to the data from this study.

This approach shows that for a 2MW and 68.000kg nacelle, the electronics weigh 900kg, or what is the same 1.32% of the total weight (Alsaleh & Sattler, 2019). On the other hand, a nacelle of 1.65MW and 51.000kg, uses 300kg of electronics, 0.59% of the total weight (Schmidt, 2006). This shows a big difference in the use of electronics for a difference of power and weight that is not that prominent. Thus, it is assumed that the bigger the turbine the more electronics are needed and thus, 2% of electronic weight is assigned to the overall weight of the turbine used in this project. From the Alpheus project it is known that the weight of a turbine will be around 264800kg, which translates to 5300kg of electronic material per turbine.

Following the same logic as Alsaleh & Sattler (2019), the ecoinvent process of 'electronics, for control units' has been used.

2.3.3.2.3 Transformers

Transformers are necessary to increase the voltage of the electricity. This is done to reduce the losses in the transmission line when transporting the electricity from point A to point B, especially at long distances. This project stores electricity, or what is the same, consumes and produces electricity offshore, which makes a transformer most likely needed for this project.

Similarly, to the electronics part, there is no information from the Alpheus project in this regard and estimations from literature had to be made. First, the transformer needed to be sized, from the results from Molina-Gomez et al (2022), when the capacity of the wind farm is 910MW, the transformer size is 400MVA. Following the line of Figure 10, it is estimated that for a plant of 2000MW, the transformer needs to be 880MVA. This information together with the indications of Jorge et al. (2012), two transformers of 500MVA from ABB (ABB, 2003) are used to extrapolate the weight of the transformer needed for this project. This technical datasheet shows the materials need for the transformer (Figure 11). From this table, it is important for the column kg/MVA, since this allows us to estimate the weight per MVA of the final transformer. However, since the table is itemized, it allows to compare the materials present in the transformer from ABB and the transformer proxy from ecoinvent. After that comparison, it is seen that the materials in both lists are different, some of the listed items in the ABB datasheet have a similar item in the ecoinvent database (as is the case of steel, insulation material, coper and paint). However, there are three other items that do not fit in any category from the ecoinvent model (wood, transformer oil and other). Then, it is decided to ignore the weight of these last items, because if done otherwise it would mean that the weight of wood in the ABB transformer could be considered as copper or steel in ecoinvent. Knowing this, the data from the ABB datasheet (kg/MVA) is multiplied by 880, which is the MVA estimated for the LH PHS plant for each of the materials that are present in the ecoinvent process. After this, their weight is summed and the resultant 354.285kg is used in the ecoinvent process 'transformer, high voltage use'.

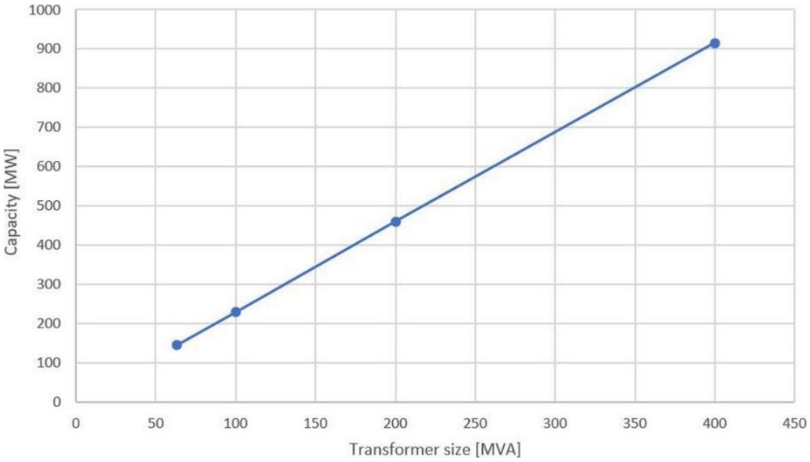
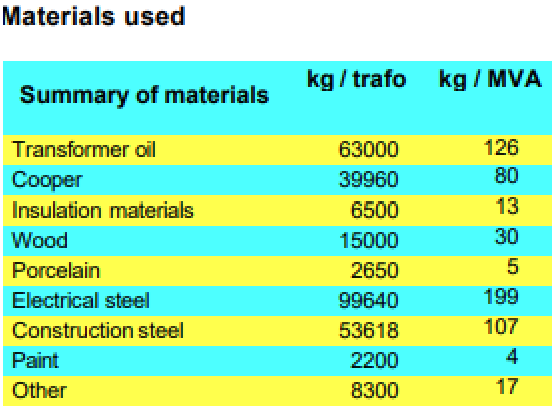


Figure 10. Trend of Transformer size and its Capacity (Molina Gómez et al., 2022).



Materials used

Summary of materials	kg / trafo	kg / MVA
Transformer oil	63000	126
Cooper	39960	80
Insulation materials	6500	13
Wood	15000	30
Porcelain	2650	5
Electrical steel	99640	199
Construction steel	53618	107
Paint	2200	4
Other	8300	17

Figure 11. Technical details of the transformers on which this research is based (ABB, 2003).

2.3.3.2.4 Subsea cables

As a storing electricity infrastructure, it is necessary to also release the electricity to the shore, and for this reason, subsea cables are necessary. It could be assumed that the LH PHS plant would use the same cables that are laid for the offshore wind farms, however, it is decided to assume the deployment of a cable only for this project. Also, 60km of cable is assumed to be used, even though the distance between the planned site and the shore is 45km. The process from ecoinvent 'transmission network construction, electricity, high voltage direct current subsea cable' is used. This process takes into account the production, laying, maintenance and decommissioning of the cable, which provides a complete estimation of the impacts for this item.

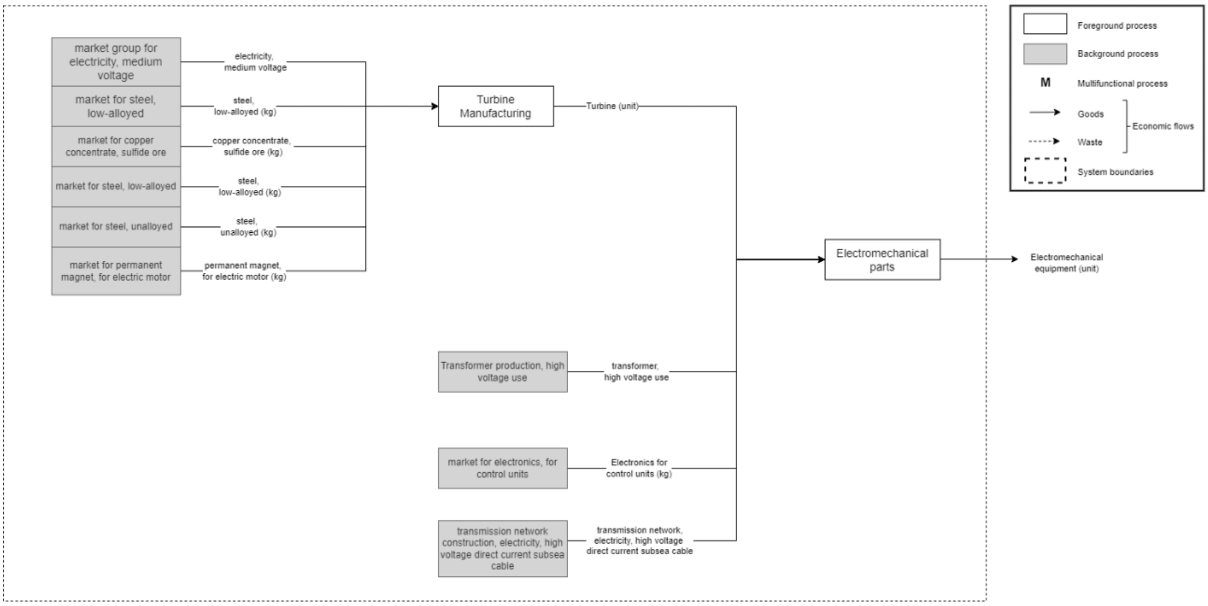


Figure 12. Flowchart of the Electromechanical equipment for the LH PHS alternative.

2.3.3.3 Maintenance

Maintenance is needed because there is some deterioration of the physical conditions of the machinery and infrastructure due to the normal functioning of the plant over time. Due to this deterioration, some actions need to take place to keep both machinery and infrastructure working properly. Below the maintenance required for the dam and the machinery are detailed and depicted in a flowchart in Figure 13.

2.3.3.3.1 Civil infrastructure

Conservatively it is common to estimate 2-3% of the initial project investment to annual O&M costs (S. Zhang et al., 2015). Since costs are not part of this report and because this data is not available, 1% of the rocks and the works needed for the protection layer are taken into account for Maintenance purposes. Besides this and following the guidance from the project designers, 10% of the sand considered for the inner berm is considered to be replaced due to settlement. Only the protection layer and the inner berm are taken into account because it is considered the only parts of the dam that can be repaired adding more material. Differently, in the case of the Caissons or the Foundations, if something went wrong and repair was needed, the materials and works needed will differ depending on the type of accident or breakage. This is something that could be deepen in further research.

2.3.3.3.2 Electromechanical equipment

The maintenance for the electromechanical equipment is more straightforward than the one considered for the dam. In this case, it is estimated that this equipment has a lifetime of 25 years. This means that, if the dam is considered to be planned for 100 years, this equipment will have to be replaced three times. All the electromechanical devices, turbines, transformers, electronics and sea cables are considered to be substituted three times in the maintenance process.

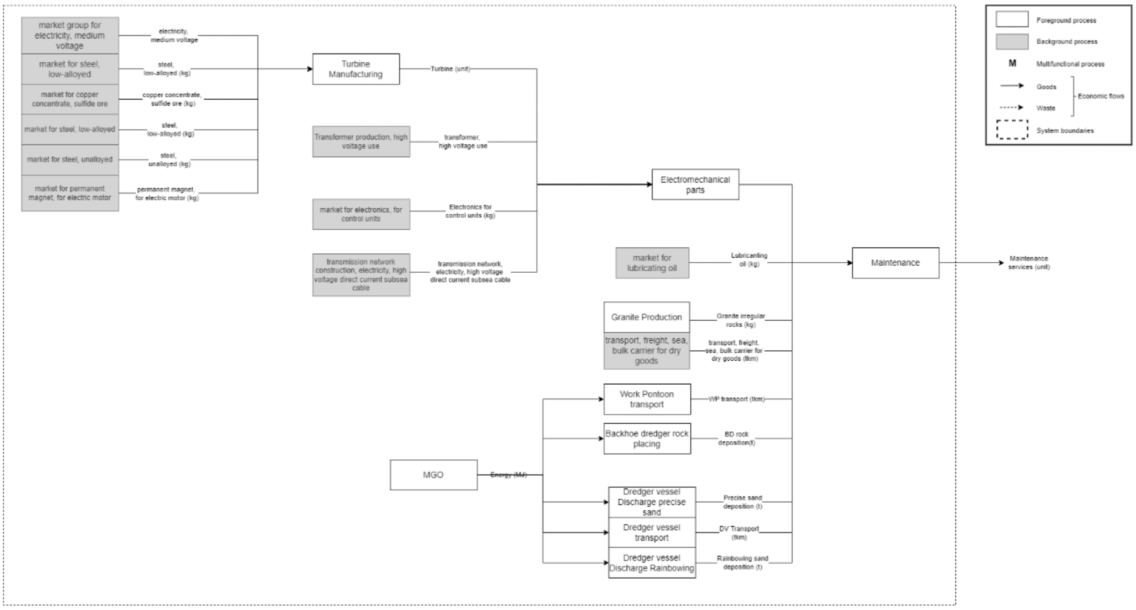


Figure 13. Flowchart of the Maintenance stage for the LH PHS alternative.

At the same time, lubricating oil was considered since it is one of the repeating relevant polluting processes that are mentioned by Gemechu and Kumar (2022). For estimating this number, values from other studies are taken into account (Briones Hidrovo et al., 2017; Pang et al., 2015). The plants studied in these papers are 3.2MW, 21MW and 43 MW and the consumption of kilogram of lubricant per MWh are 3.2e-2, 1.06e-3 and 4.91e-4 respectively. As can be seen, there is a trend of using less lubricant as the plant gets bigger. Each plant consumes one order of magnitude less than the previous and smaller PHS plant. Following this trend, the amount of lubricant considered for this study is two orders of magnitude smaller than the lubricant needs for the 43MW plant, 4.91e-6kg/MWh. Then, this number is multiplied by the electricity production in the whole lifetime of the plant, 2.92e11 MWh, resulting in 1430 tons of lubricant needed for the whole lifetime of the LH HPS plant.

2.3.3.4 Operation

In this stage is important to highlight the fact that this study is based on the assumption that biogenic emissions do not happen, at least not at the same magnitude as in traditional PHS. This is important for the operation part because it is thought that these emissions play a relevant role in the overall impact of the plant, especially in tropical areas, as shown in Figure 14 (Gemechu & Kumar, 2022). This assumption is taken because these emissions start from the fact that an area of land is flooded, leaving underwater large amounts of organic matter, which decomposes over time and releases GHG. This fact however does not happen offshore, since the area is already covered by water.

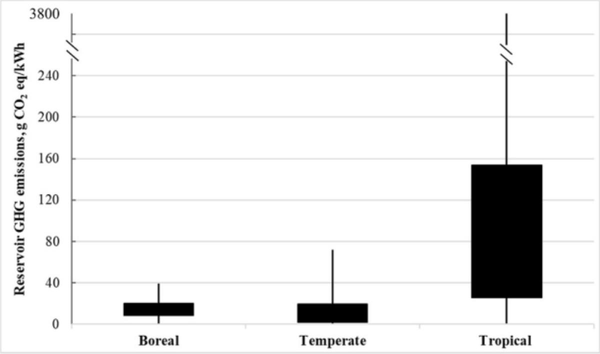


Figure 14. Reservoir GHG emission ranges for hydropower in different climate zones (Gemechu & Kumar, 2022).

It is considered the operation of all the actions, works and tasks that happen as the result of the normal functioning of the plant. Thus, the emissions resulting from the operation of the plant will be very few. More concretely, only the fugitive emissions of sulfur hexafluoride (SF6) resulting from the use of the cooling system and the transformers (Verán-Leigh & Vázquez-Rowe, 2019) are taken into account. These emissions have been estimated by taking the value from Verán Leigh & Vázquez-Rowe (2019) of 3.4e-10kg/kWh, which multiplied by the total electricity produced results in 99.28kg of SF6 for the whole lifetime of the plant.

On the other hand, before storing energy in the LH PHS plant, electricity has to be produced. This process does have emissions, these emissions can come from different places, as a result of the production of windmills or from the burning of coal, for example. The amount of electricity that has to be produced is bigger than the electricity finally delivered by the LH PHS plant. This is because there are some efficiency losses in the process of pumping the water up and producing electricity from spinning the turbines. Thus, depending on the efficiency of the plant the amount of electricity that will be lost will vary. Because of this fact, this study differentiates the emissions resulting from the production of electricity that is lost and the effective electricity that is delivered. More precisely, this project is based on the assumption that the LH HPS has an efficiency of 70%. The flowchart of this section can be seen in Figure 15.

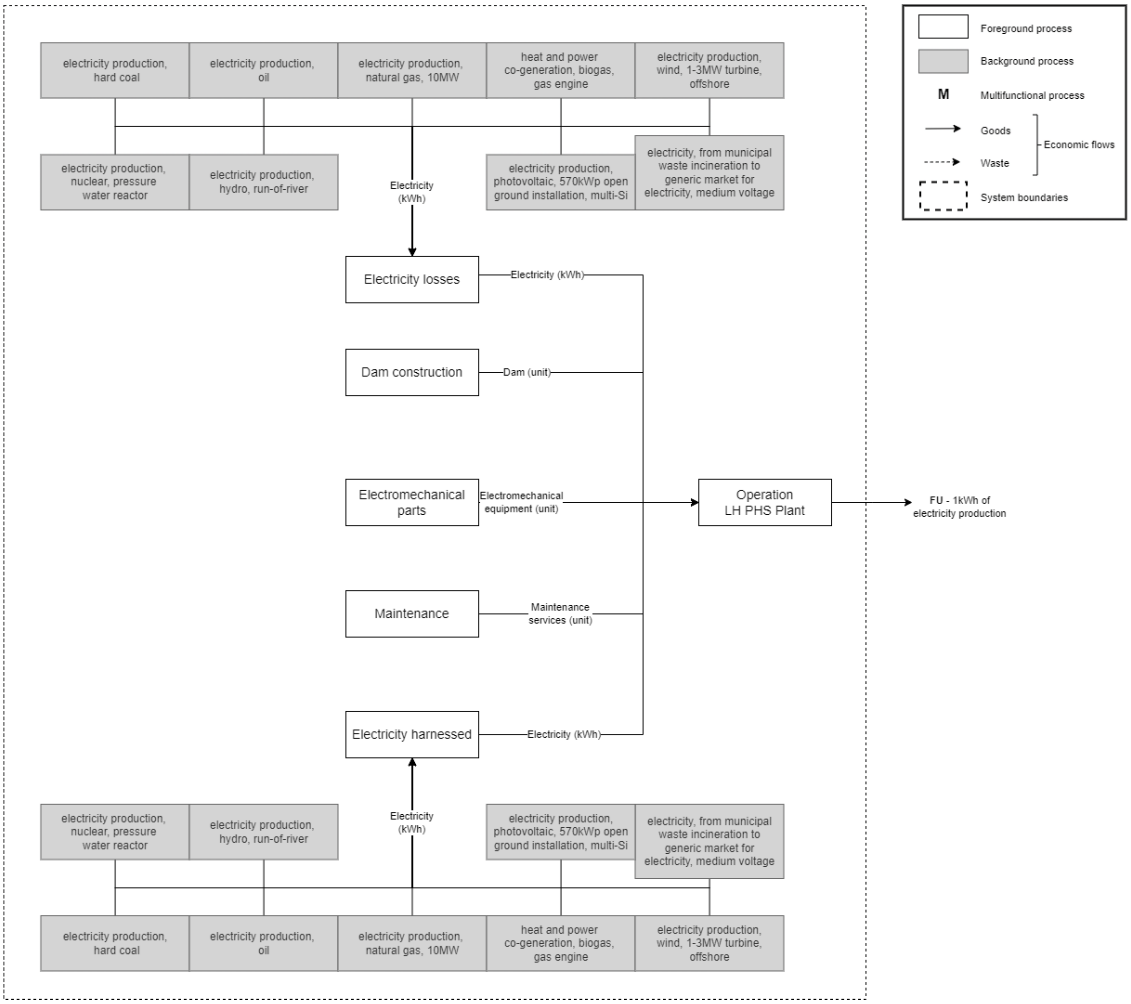


Figure 15. Flowchart of the Operation stage for the LH PHS alternative.

2.3.3.5 Decommission

Decommission GHG emissions have the root in two processes: the physical dismantling of the plant and; emissions from sedimented organic carbon, which is either produced somewhere else and flooded during construction stages or due to dead plankton inside the reservoir (Gemechu & Kumar, 2022). The first type is not mentioned in Gemechu & Kumar's (2022) work and due to information restrictions, lack of knowledge in this area and limited time, this was not further investigated, following the assumptions of other authors that consider this stage impacts minimal when compared with the construction ones. It is acknowledged that this is a simplistic approach and further research in this area should be done. The magnitude of the second type of emissions is too high to be ignored according to Gemechu & Kumar (2022). These emissions happen because the impoundment created first is dried and the soil and organic matter release GHG with the contact of air. Similarly to biogenic emissions from the operation stage, since there are no areas that are flooded and then dried, these emissions are expected to never happen and thus, are not taken into account in this study.

2.3.3.6 Complete flowchart

Below, the complete flowchart is shown in Figure 16. This is the combination of the previous flowcharts, considering all the parts for the contruction, operation and maintenance of an LH PHS plant.

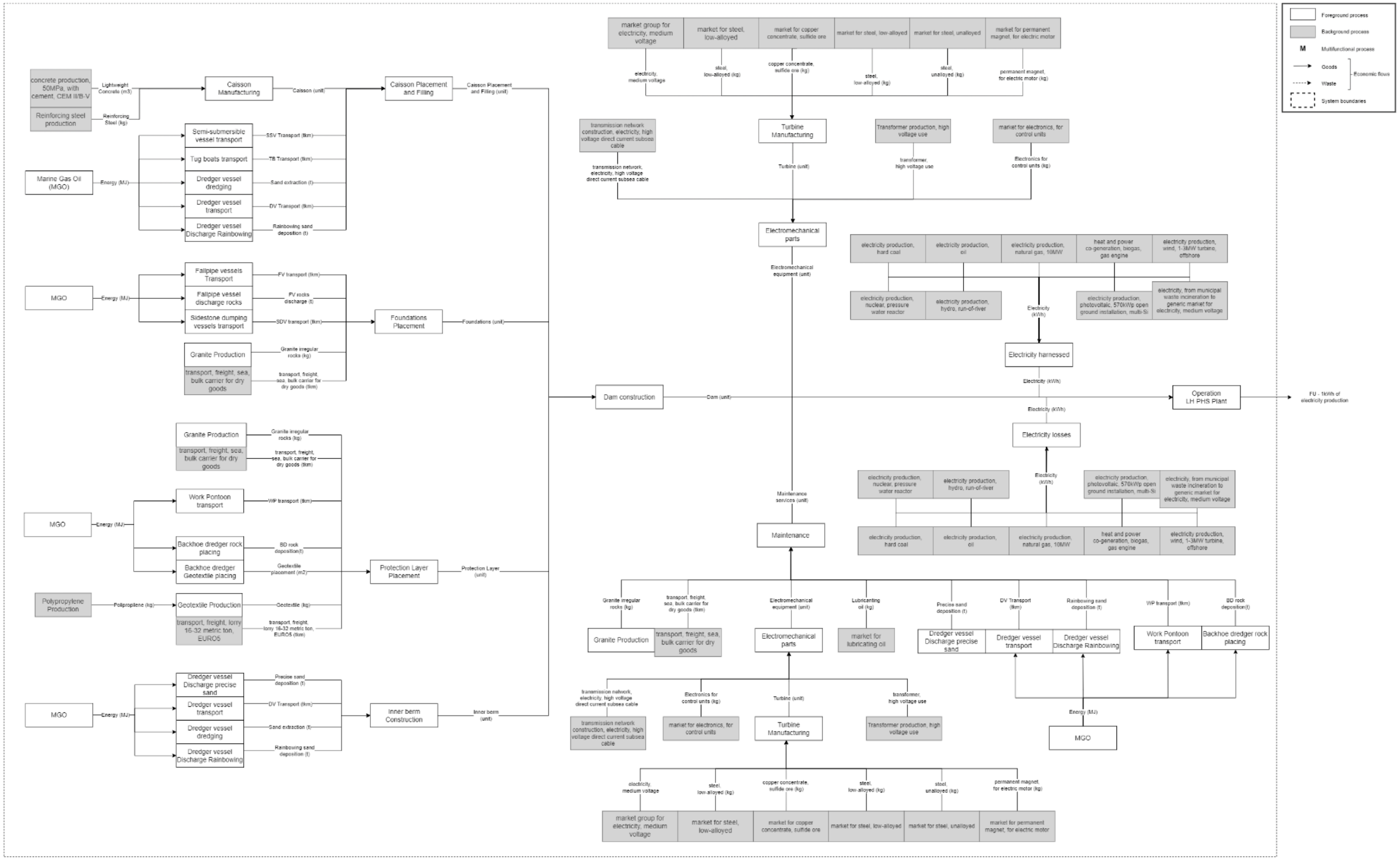


Figure 16. Complete flowchart with all the stages included for the LH PHS alternative.

2.3.4 Li-ion batteries

Li-ion batteries are a common type of battery for all kinds of electronic devices. However, there are several types of Li-ion batteries. To select the specific type of battery to be used in this study, the first step was to see which are the possibilities in the ecoinvent database. After knowing this, research on these types of batteries and their use has been done. It was found that the specific characteristics of Li-ion battery types of Lithium iron phosphate (LFP), Nickel cobalt aluminium (NCA) and Nickel manganese cobalt (NMC) fit the requirements for Grid Storage application (Killer et al., 2020). However, the costs of LFP are lower than the other alternatives (Fan et al., 2020), moreover, it is also assumed that batteries manufacturers will move away from conflictive materials like cobalt. For these reasons, LFP batteries are the type of batteries chosen to be compared.

Batteries' performance changes with time, the more they are used, the more they lose capacity. Degradation of the cell and thus, the worsening of the battery properties like efficiency and lifetime depend on the depth of discharge (DoD), charging rate and temperature (Peters et al., 2017; Swierczynski et al., 2015). It is usually assumed that batteries are only used while they perform over 80% DoD efficiency (Gallo et al., 2016; Hosen et al., 2021; Peters et al., 2017; Popp et al., 2014). However, this study aims to provide a range of values for the environmental performance, and for that, the lifetime and efficiency of the batteries are used as the main variable to play with.

For the modelling, a range of efficiency values is assigned, just like for cycle lifetime. The average is selected at 92.4%, the best-case scenario at 99% and the worst-case scenario at 80% (Peters et al., 2017). Which translates into an electricity output of 2920 GWh/year and electricity losses of 240 GWh/year.

It is assumed batteries will have a full cycle per day, providing the same performance as the LH PHS plant, 8GWh per day and an expected lifetime of the plant of 100 years. It is not possible to justify the use of one number cycles lifetime since different literature presents different values (Chen et al., 2012; Gallo et al., 2016; Lehtola & Zahedi, 2021; Peters et al., 2017; Popp et al., 2014; Swierczynski et al., 2015). To make up for this and considering that future trends will most likely happen in this area, increasing the lifetime of Batteries, a range between 15-25 years (with an average value of 20 years) of lifetime is assigned, which goes in line with the literature on the topic (Dufo-López et al., 2021; Gasper et al., 2022; Keil et al., 2015). This is the same as saying that for those scenarios, the batteries will have to be changed 6.7, 5 or 4 times. This information together with the specific energy capacity (kWh/kg) of the battery provided in ecoinvent, allows the calculation of the total battery needs per type. LFP batteries have a specific energy capacity of 0.159kWh/kg, which translates into 50314.5 tons of battery per plant and replacement. The flowchart of this section can be seen in Figure 17.

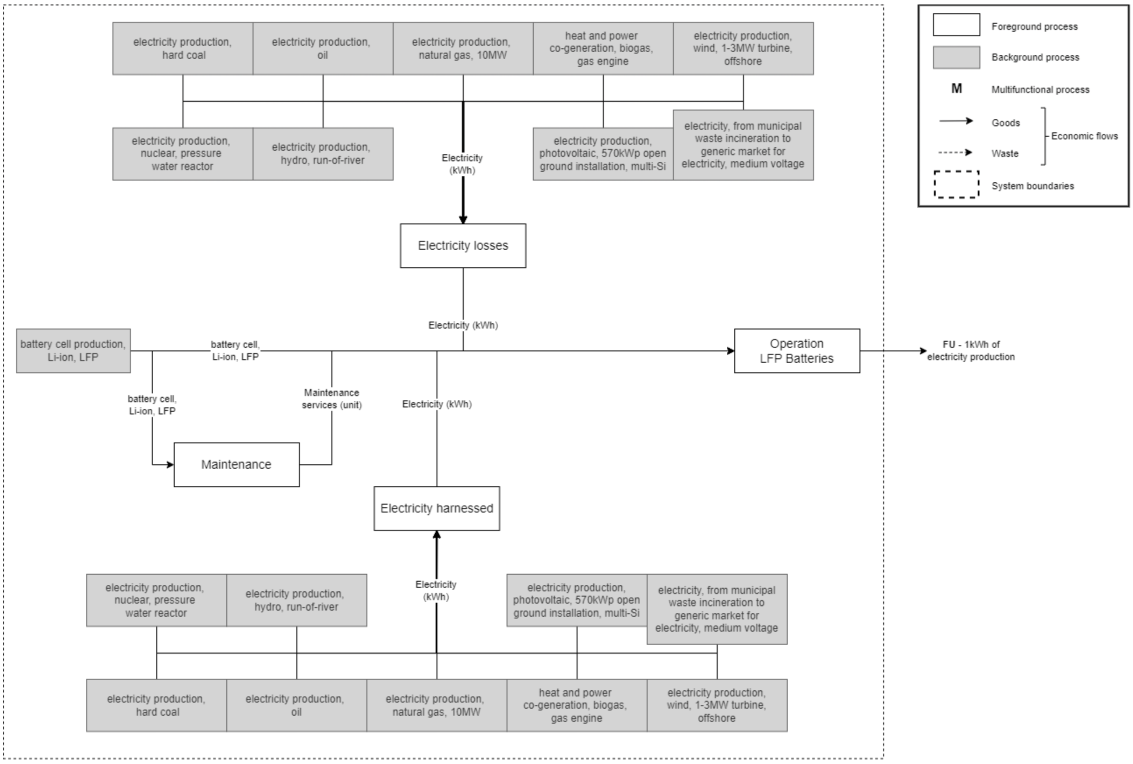


Figure 17. Flowchart of the Li-ion LFP Batteries alternative.

2.3.5 Green H2

Different the Li-ion batteries, there is no proxy for energy storing and generation with green hydrogen. Although it is acknowledged that the infrastructure needed for the production, storage, transport and electricity generation from hydrogen would have a relevant role in the environmental impact. Because it was not feasible to model its infrastructure due to time restraints, only the electricity needs have been taken into account for the hydrogen production and the electricity generation from hydrogen (see the flowchart in Figure 18). Since no infrastructure has been considered, there is not any flow for maintenance or operation either. This fact makes the model to be different that those of the LH PHS and Li-ion batteries in its structure. Instead of considering the whole lifetime of infrastructure for 100 years, the model for H2 is made for 1kWh of output.

However, the two processes considered here have different efficiencies and this is the main factor that plays a role in the model. The production of hydrogen has been modelled with intakes from wind electricity and a range of efficiency between 63-82% (Osman et al., 2022). This range refers to the production of hydrogen from alkaline electrolysis, which is the process that considers water as feedstock with the highest energy efficiency according to Parra et al. (2019). The production of hydrogen from this process is quantified in kWh for the sake of simplicity. Then, electricity generation is fuelled by hydrogen with an efficiency of 51.3% (Ozawa et al., 2019). This percentage is taken from the assumption that electricity is produced in a mono-firing thermal power plant. This concludes in a final efficiency of 31.3%-42-1% for the whole process.

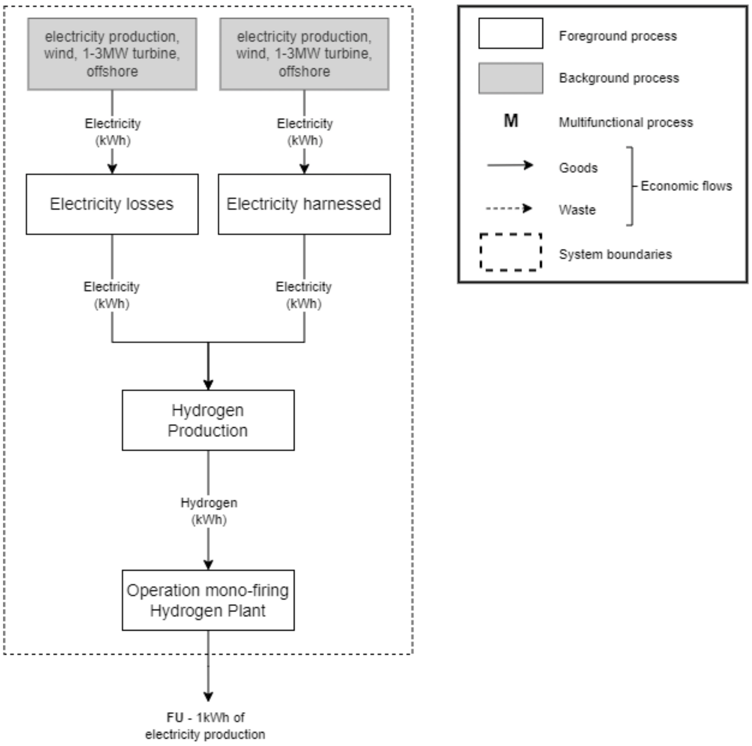


Figure 18. Flowchart of the Hydrogen alternative.

2.3.6 Multi-functionality and allocation

The final models for the three alternatives have in common that there is no waste, allocation and multi-functionality. This means that the model itself is quite simple, even though the complete model of the LH PHS system contemplates many processes and our model clearly is an underestimation of the real impacts to be expected.

2.4 Impact categories

For the selection of impact categories, this report is based on the directions of the European Commission Recommendation 2021/2279 (2021) " on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations". More specifically point 3.2.3, where a default list of impact categories for Product Environmental Footprint (PEF) studies is presented, see Table 3.

Although calculations for 16 different impact categories are done, only Global Warming Potential, Water Use Deprivation Potential and Abiotic Depletion Potential-Elements are analysed and discussed in this report. The results for the rest of the categories are written in

Annex 1 for transparency purposes and in case someone would like to thoroughly analyse the project in the future.

Table 3. List of all calculated impact categories with their abbreviations and units (THE EUROPEAN COMMISSION, 2021). Highlighted, those categories that have been thoroughly assessed in this report

Category indicator	Abbreviation	Unit
Global warming potential	**GWP**	kg CO2 Eq
Ozone depletion potential	**ODP**	kg CFC-11-Eq
Human toxicity: carcinogenic	**HTC**	CTuh
Human toxicity: non-carcinogenic	**HTNC**	CTuh
Particulate matter formation	**PMF**	disease incidence
Ionising radiation: human health	**IR**	kBq U235-Eq
Photochemical oxidant formation: human health	**POF**	kg NMVOC-Eq
Acidification - accumulated exceedance (AE)	**AE**	mol H+-Eq
Eutrophication: terrestrial	**ET**	mol N-Eq
Eutrophication: freshwater	**EF**	kg P-Eq
Eutrophication: marine	**EM**	kg N-Eq
Ecotoxicity: freshwater	**EXF**	CTUe
Land use - soil quality index	**LU(Q)**	dimensionless
Water use - user deprivation potential	**WUDP**	m3 world eq deprived
Abiotic depletion potential (ADP): elements (ultimate reserves)	**ADP-E**	kg Sb-Eq
Abiotic depletion potential (ADP): fossil fuels	**ADP-F**	MJ, net calorific value

This can also be justified because the whole energy transition is purposed to reduce Greenhouse gases, and the purpose of LH HPS is to be presented as a part of the solution for the energy transition. Furthermore, it has been widely discussed that for this energy transition materials use is critical, and analysing the resources is key (Ali et al., 2017; Calvo & Valero, 2022; Toro et al., 2020). And finally, water scarcity has been a problem that has affected billions of people for a long time now (Mekonnen & Hoekstra, 2016; Rijsberman, 2006) and is becoming with time a more urgent and tangible problem.

Besides the aforementioned impact categories, additional technical information like the Bill of Materials will also be considered and discussed as well as the energy density and the land use of the different alternatives.

Although the concept behind the results from GWP and WUDP seems familiar and logical to understand, ADP-E may not be that straightforward. Thus, it seems appropriate to delve further into this concept before showing the results. The ADP-E method was based on the global scarcity of materials, mainly considering world annual production and the estimated ultimate global reserve (Van Oers et al., 2020). In the same way, CO2 works as an equivalent for the global warming potential that different gasses may have in the atmosphere, one element (Antimony (Sb), in this case) is used in the chosen framework to represent the different elements, which have different weights depending on their scarcity. As a side note, might be important to highlight that Sb is not chosen because of its unique properties but because it serves as a practical reference point.

2.5 Scenario set up

2.5.1 LH PHS Infrastructure

First of all, it is important to see the environmental impact of LH PHS infrastructure. This has been modelled following Figure 16 flowchart, but without considering the electricity inputs nor the efficiency of the turbines. In other words, the processes 'Electricity harnessed' and 'Electricity losses' have been ignored for this simulation. Also worth mentioning is the fact that in this simulation there is no comparison with any other scenario. This will come in later stages of the report.

The results will then, derive directly from the Dam construction, the Electromechanical equipment and the Maintenance of the plant. This is done to provide a full picture of the project and to zoom in to know where the impacts are in the infrastructure, which is important for its development of it.

2.5.2 LH PHS Electricity Scenarios

It seems relevant to see the impacts the infrastructure has compared with the impacts of the electricity used for storing electricity. For this, an approach of scenario LCA has been used, where, following the flowchart pictured in Figure 16, electricity comes from different sources. Depending on the scenario these sources have been given more or less weight. The different scenarios in the simulation consider the infrastructure with wind electricity or with the Dutch electricity mix of 2021. For the wind scenario, only electricity input from offshore wind farms has been regarded as input, and finally; for the final scenario, the shares of the Dutch electricity mix from 2021 have been modelled. These electricity inputs are chosen for two reasons. The first reason is that it is considered that these are the two most realistic sources of electricity in which the plant would be powered. Due to the location and the plans for building new offshore wind farms (as depicted for the area plans in Figure 5 and 6 with the orange areas called "Planned windfarms"), it is logical to assume that the goal of the plant is to store wind electricity during peak production times. On the other hand, it is also logical that sometimes grid electricity will be used to pump water upstream the reservoir. Moreover, because it is not possible to know the proportions of the future electricity mix, a conservative approach is assumed with the grid mix of 2021. The second reason is because they represent the best- and worst-case scenarios. The wind-sourced electricity is considered the environmentally best-performing electricity production technology (Asdrubali et al., 2015), while the Dutch electricity mix from 2021 (see Table 4) is considered the worst-case scenario because it is assumed that, due to the energy transition, electricity sources will only get greener. Wind energy was used under the name of 'other renewables' instead, raising its share to 15.01%. This, in any case, goes in favour of this alternative, making it 'less bad'.

Table 4. Dutch electricity grid mix from 2021, itemized by type of energy source and its percentage share. Average taken from (IEA, 2022; Ritchie et al., 2022).

NL average grid mix for 2021	
Coal	13.12%
Oil	3.05%
Gas	46.55%
Bioenergy	8.02%
Waste	1.63%
Nuclear	3.15%
Hydro	0.07%
Solar	9.39%
Wind	14.80%
Other renewables	0.21%

Besides the electricity input, all the conditions of the plant remain the same, electricity production, dam and equipment lifetime, maintenance needed, etc. Moreover, there is an efficiency that is needed to be taken into account. This has been modelled by having two electricity inputs in the Operation process: the electricity that is ultimately used and the losses of the process. The proportions are the same for the two alternatives presented, 70% efficiency since this number is a consequence of the plant itself and is not conditioned by the source of electricity used as input.

2.5.3 Comparison with other Storage Technologies

Because LH PHS is not the only energy-storing technology, it is considered important to compare this technology to relevant alternatives. In this case, the LH PHS plant has been compared with LFP Li-ion Batteries and Green Hydrogen. It can be seen in their flowcharts depicted in Figures 16, 17 and 18 how these three technologies are modelled. As mentioned in the inventory analysis, a simplistic approach with proxies is used to model LFP batteries and Green Hydrogen. For LFP batteries, only the batteries themselves have been taken into account as part of the infrastructure whereas for the Green Hydrogen alternative, only the electricity requirements for the production of Hydrogen and the generation of electricity are taken into account. At the same time, there is another difference in the approach taken for LFP batteries and Green Hydrogen. It is considered that batteries can be charged by the same sources of electricity as the LH PHS plant, meaning wind power and the 2021 Dutch electricity mix. On the other hand, it is only considered Green Hydrogen produced by the wind; due to the wide variety of Hydrogen colours (and their technology specifics), it is considered not feasible to model all of them. Moreover, considering Green Hydrogen produced from wind energy is considered the best alternative in environmental terms. This fact is also important because the technology comparison presented in this study is a scenario-based LCA where efficiencies and electricity sources vary. Thus, considering the last statements, Green Hydrogen results will be only present for the scenarios when they are powered by wind power.

For LH PHS it is assumed a range between 60% to 80% roundtrip efficiency, with an average of 70%; for LFP batteries, according to Peters et al. (2017), a range between 80% and 99% is selected with an average battery performance of 92.40%. Moreover, LFP Batteries have another variable to take into account that directly influences the environmental performance of the technology, the lifetime of the battery. This variable has also been given a range with an average of 20 years as average, 15 years as the worst-case scenario, and 25 years cycles for the best-case scenario (Swierczynski et al., 2015). It is considered that after that time the old batteries are replaced with new ones. Finally, for Hydrogen, two efficiencies are considered, one for the alkaline electrolysis to produce Hydrogen from water and the second for the production of electricity from a mono-firing plant fuelled by Hydrogen. The first one is considered between 61% and 82% with an average efficiency of 71.5% (Osman et al., 2022). The second efficiency does not consider a range of values but just one, 51.3% (Ozawa et al., 2019). These two efficiencies together make a roundtrip efficiency between 31.29% and 42.07% with a middle point of 36.68%.

3 Results

3.1 Impact assessment

Results in this section are divided in three parts. The first ones talks about the results on the LH PHS infrastructure; the second one considers LH PHS infrastructure and the electricity requirements to make it work and; the third part compares the results of the LH PHS infrastructure with its electricity inputs with other technologies: Li-ion LFP Batteries and Green Hydrogen. At the same time the results of these parts are subdivided in three segments where the focus is put in the different impact categories: GWP, WUDP and ADP-E, where the results and a contribution analysis is done.

In this study the contribution analysis is performed to find hotspots (ISO, 2006), moreover, it is also performed to understand how the model works and why some changes affect, and to which degree, the performance of the different indicators following the same structure, only results on GWP, WUDP and ADP-E are presented. These results will be depicted with bar graphs and Sankey diagrams in this section, some of these diagrams have a 10% cut-off (this means that only processes with more than a 10% participation are shown) and are cropped to make them big enough to be readable. These diagrams in their complete version are provided in Annex 1.

When looking at the graphs below, it is important to remember that in any case, they represent the absolute value of the emissions for any category indicator. They show the processes that are major contributors to the emissions of the different scenarios on a percentage scale. This means that, even though the absolute emissions for the different scenarios are different, the graphs will be scaled to 1 and major contributors will be depicted with their respective share.

3.1.1 LH PHS Infrastructure

Absolute values of the infrastructure emissions can be seen at Table 5. Although the numbers itself do not seem high, the unit of these emissions should be highlighted. For GWP it is estimated that the plant construction, maintenance and operation of the plant will emit 2.8Mt of CO2-eq, which would be equal to almost 2% of the total emissions from The Netherlands in 2021 (Ritchie et al., 2020). In terms of water 0.6km3 will be needed. This is 601 million m3, which was half of the water consumption of The Netherlands in 2019 (CBS, 2021). Finally, it is estimated that 140.2 tonnes of Sb-eq will be needed. This number is a bit more difficult to translate in tangible equivalent, and therefore, Table 6 is attached with the total material requirements for the plant. Here it can be seen that the LH PHS plant needs important inputs of concrete, steel, sand and granite for the civil infrastructure, whereas important amounts of different types of steel copper and magnets are needed for the electromechanical part. These results are manually estimated t for the civil and electromechanical infrastructure, these calculations can be found in Annex 2. These outcomes, shown in Table 6, demonstrate the scale of the project, where almost 25 and 2.5 million tonnes of granite and concrete are needed. At the same time, 122 million tonnes of sand are estimated to be used for the inner berm and for filling the caissons. However, this material is assumed to be extracted from the seabed, due to its location (45km away from the Dutch shore) it is assumed that does not compete with the production of construction products like concrete, since sand for concrete is usually extracted from river beds or quarries (Torres et al., 2021). On the other hand, it is needed more than 150.000 tonnes of unalloyed and stainless steel for the civil and electromechanical infrastructure.

Table 5. Absolute emissions for the LH PHS Infrastructure

	Absolute emissions	Unit
GWP	2.8	Mt CO2-eq
WUDP	601	Million m3 water-eq
ADP-E	140.2	t Sb-eq

Table 6. Material requirements for the LH PHS alternative.

Material requirements for LH PHS plant

Civil infrastructure materials for 100 years			**Electromechanical equipment materials for 100 years**		
Concrete	2,532,288	tonnes	Electrical steel	11,326	tonnes
Steel	158,268	tonnes	Copper	11,326	tonnes
Sand	122,702,091	tonnes	Stainless Steel	157,072	tonnes
Granite	24,682,331	tonnes	Steel	31,554	tonnes
			Magnet	555	tonnes

3.1.1.1 Contribution Analysis

3.1.1.1.1 GWP

Figure 19 depicts the processes that contribute the most to GWP for the LH HPS infrastructure. More in detail, material needs like Granite, Clinker or pig iron plays a major role. Even transport, which is an indirect process influenced by the infrastructure's material use, plays an important role. Nonetheless, ‘electricity needs’ is the process that emits most of the CO2-eq emissions when only the infrastructure is considered, due to the electricity needs that the production of the materials have.

When looking at the Sankey diagram (Figure 20) it is visible that the construction of the Dam (considering only civil infrastructure) contributes to 55.7% of all the emissions; whereas the electromechanical equipment needed at first presents a weight of 10.9% and the recurring replacement of this equipment through the lifetime of the dam emit 33.2% of the whole infrastructure. This finding gives almost an equal ‘responsibility’ for the emissions to the civil and electromechanical parts of the project, which should be taken into further consideration. This is a surprising fact, as from the start of the project it was thought that the overwhelming majority of the emissions would come from the civil infrastructure, more specifically from concrete production. In reality, the process that contributes the most to CO2-eq emissions is the production of the rocks placed in the foundations and the granite protection layer. The data for this process is extracted from literature and it might be relevant for further research to check this fact.

Actually, if the emissions are split by material, granite production reaches 21.6% of the emissions, whereas stainless steel emits 28% of the total, concrete 17% and reinforcing steel 11.8%. However, since granite production is not a background process but one made specifically for this project, these emissions are not divided by the electricity needs, the material ones and the transport, but are gathered as one process. This explains why in Figure 20 granite stands out as the material and stainless steel does not.

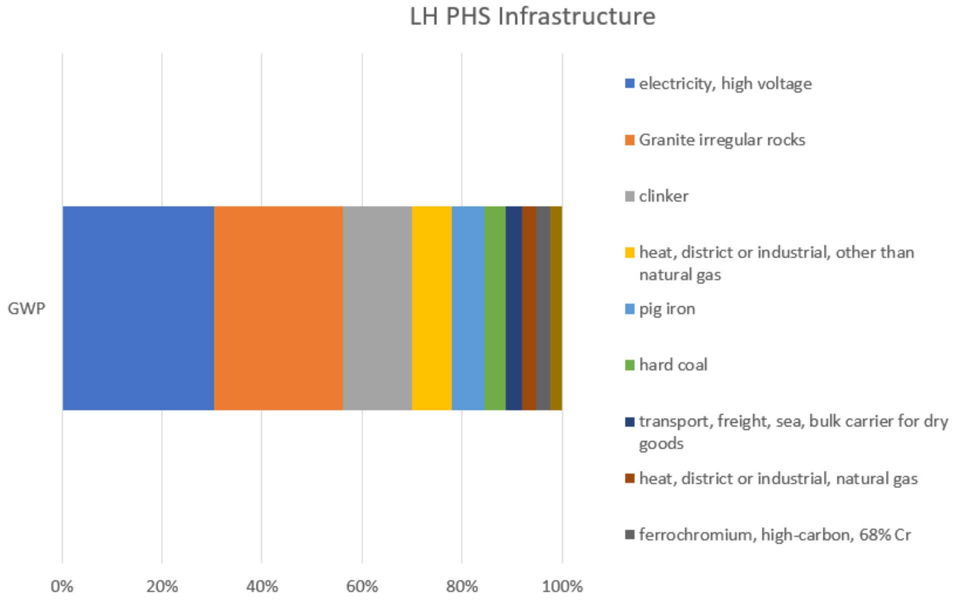


Figure 19. GWP contribution for the infrastructure of the LH PHS plant.

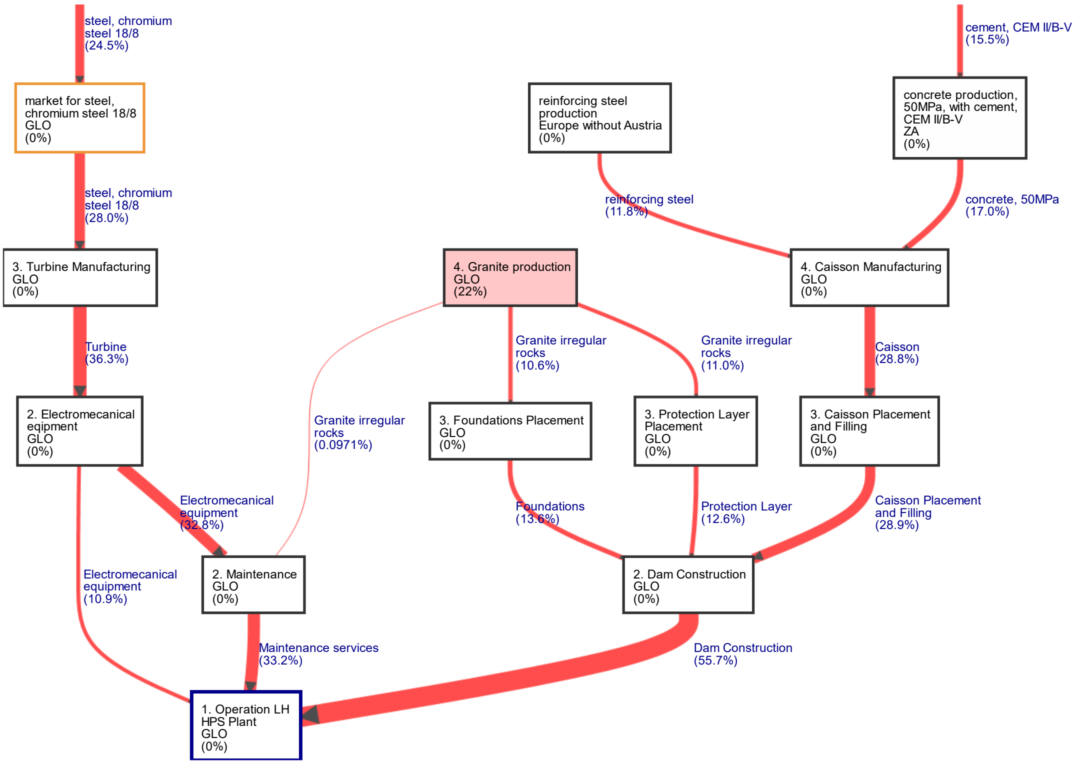


Figure 20. GWP Sankey diagram for the infrastructure of the LH PHS plant.

3.1.1.1.2 WUDP

In the scenario of analysing only the infrastructure, it can be seen that the major contributors to water depletion are electricity generation and steel production (Figure 21). These two processes may seem unrelated but when taking a closer look at the Sankey diagram (Figure 22) surprising information is revealed. Different from GWP, electromechanical equipment reaches almost 70% of the water use (between the construction and maintenance) in contrast to civil infrastructure, which is responsible for 30% of the water use. When digging a bit deeper, it is seen that steel from both civil and electromechanical infrastructure (in all its forms and alloys) accounts for roughly 62.5% of

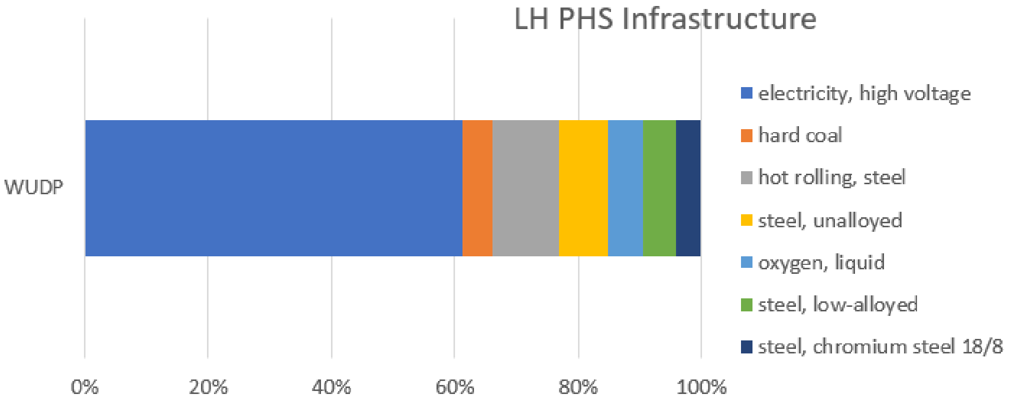


Figure 21. WUDP contribution from the infrastructure of the LH PHS plant.

water use. Thus, there is a relation between electricity generation and steel production, which is the main hotspot of water consumption.

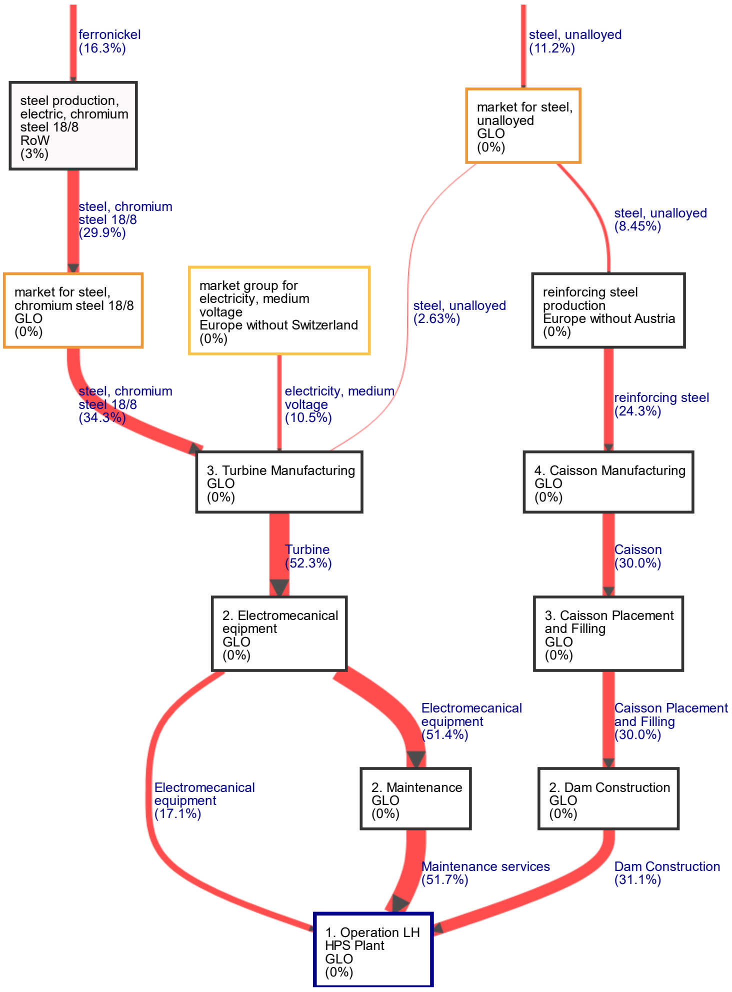


Figure 22. WUDP Sankey diagram for the infrastructure of the LH PHS plant.

3.1.1.1.3 ADP-E

As previously mentioned, Abiotic depletion of elements is a particular impact category that considers elements (minerals and metals) based on their global scarcity. Because of this fact, only a handful of metals are listed in this section whereas other elements widely used in this project are ignored, like sand or concrete, because they do not classify as scarce.

When analysing the LH PHS plant alone, as shown in Figure 23, copper, gold, chromite and lead stand out as the main contributors to this impact category. When looking deeper into detail in the Sankey diagrams (Figure 24), it conveys the fact that only electromechanical equipment is considered, ignoring the civil infrastructure. More specifically, even though electronics are not considered in the previous impact categories, here they present a major role, accounting for 33.6% of the total footprint due to the presence of gold and lead in the wiring boards. In the same line, subsea cable and the use of copper and lead also have an important weight in this section, where 23.9% of the impact is allocated in this process. Finally, turbines are the last big single process contributor, with 39.7% of the total impact, owing to the use of chromium in stainless steel and copper.

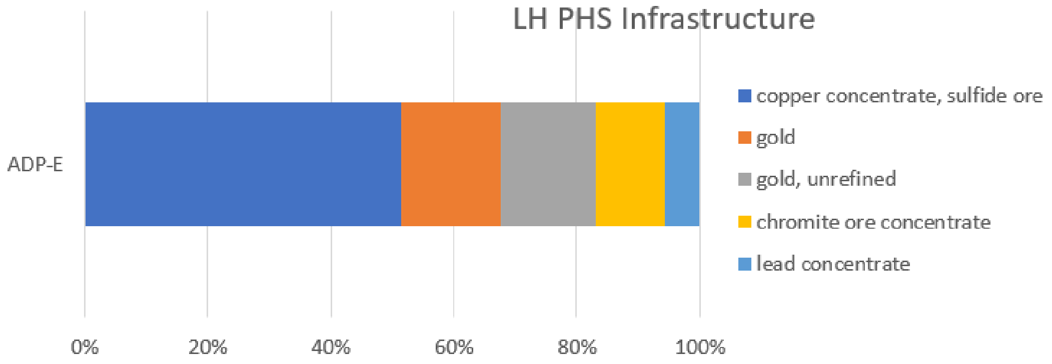


Figure 23. ADP-E contribution for the infrastructure of the LH PHS plant.

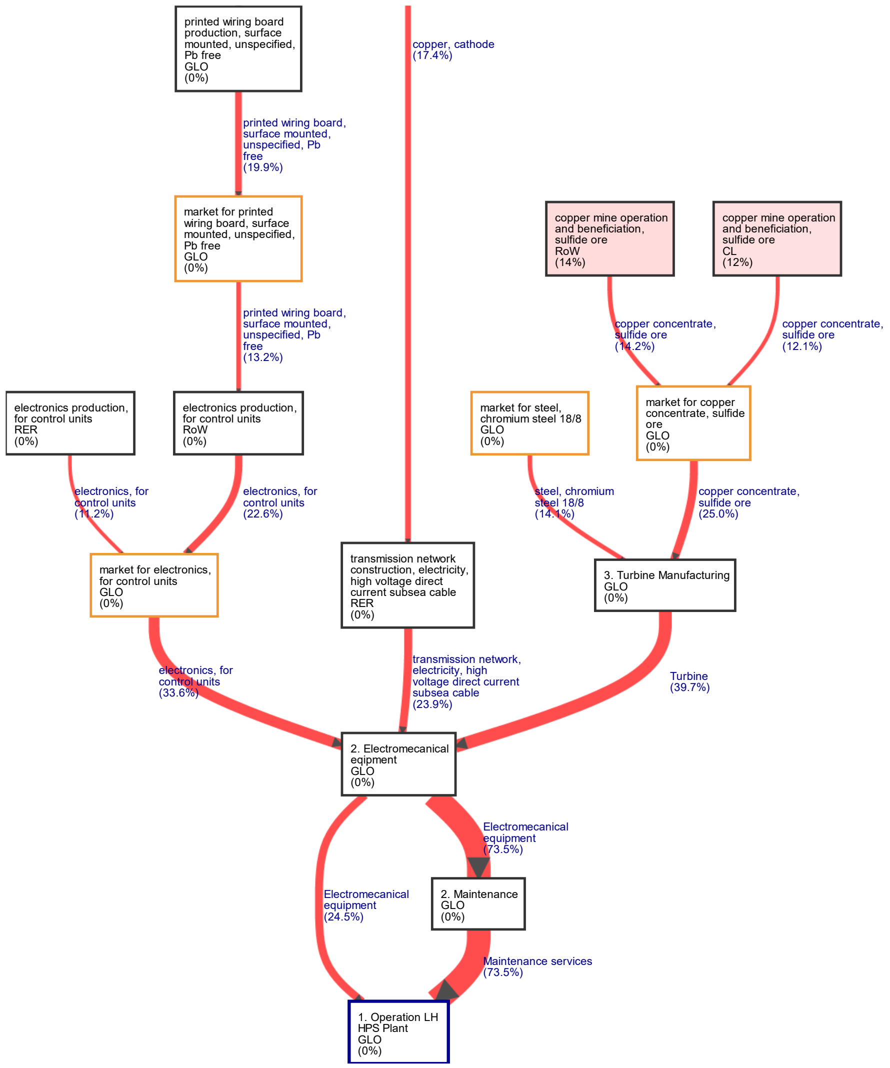


Figure 24. ADP-E Sankey diagram for the infrastructure of the LH PHS plant.

3.1.2 LH PHS Electricity Scenarios

Different to the previous section, the results shown in this section and the next one are in scale per kWh production. This means that the impacts shown below are the result of the production of 1kWh.

Results shown in Figure 25 put in perspective the scale of this LH PHS project, which although enormous in its dimensions and emissions, remains small when comparing the emissions with those resulting from the electricity production, regardless of the electricity scenario. However, in the scenario where the electricity is sourced from the grid, CO2-eq emissions and water consumption increase drastically. Whereas infrastructure has a more relevant role in the consumption of metals and elements, although is still inferior to the material needed for electricity production. Resulting from the application of the efficiency of the turbines, it can be seen the division between Infrastructure, Energy harvested and Energy lost in Figure 25 and Table 7. It is evident that the infrastructure emissions does not change with the different scenarios, whereas the energy emissions do get bigger in the NL mix 2021 scenarios in the case of GWP and WUDP.

More specifically, the footprint from the electricity production from wind (subtracting the infrastructure emissions from the total number) is 2, 5 and 1.8 times bigger than the emissions sourced in the infrastructure for GWP, WUDP and ADP-E respectively. On the other hand, when looking at the electricity sourced in the grid, these impacts rise to 77, 37 and 1.8 times for the same indicators. The results for these 3 indicators are depicted in Table 8, while in Annex 1, the results are shown for all the indicators mentioned in the Commission Recommendation (EU) 2021/2279 (THE EUROPEAN COMMISSION, 2021).

Table 7. LH PHS emissions divided by Infrastructure and Energy needs.

	Scenario	Infrastructure	Energy harvested	Energy lost	Total
GWP (kg CO2-eq/kWh)	**Wind**	0.0095	0.016	0.007	0.033
	NL mix 2021	0.0095	0.514	0.220	0.744
WUDP (m3 water/kWh)	**Wind**	0.0021	0.0081	0.0035	0.0136
	NL mix 2021	0.0021	0.0546	0.0234	0.0800
ADP-E (kg Sb-eq/kWh)	**Wind**	4.802E-07	6.005E-07	2.574E-07	1.338E-06
	NL mix 2021	4.802E-07	6.024E-07	2.582E-07	1.341E-06

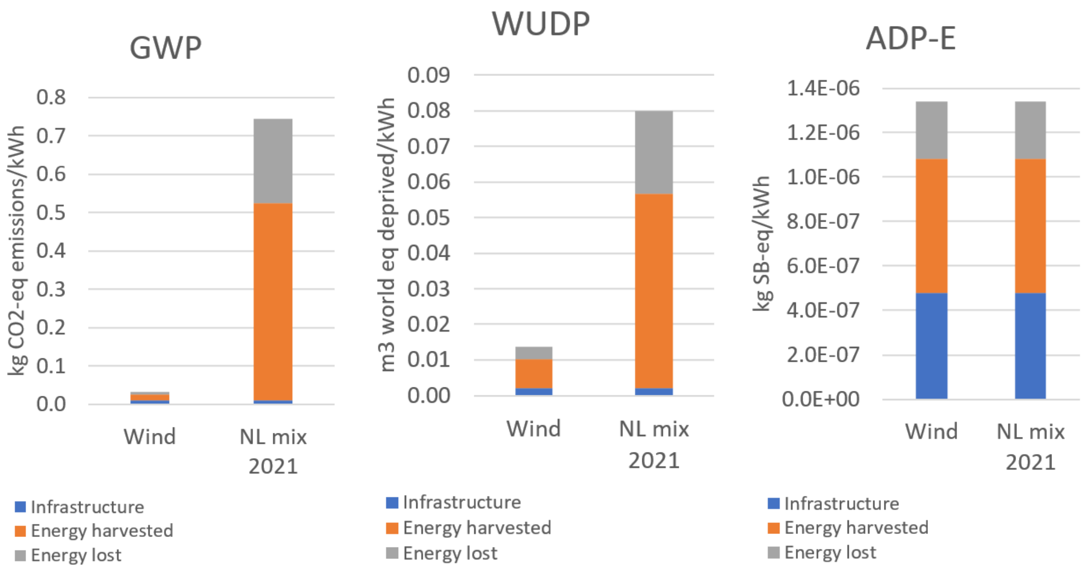


Figure 25. Results for the LH PHS plant for the two electricity scenarios: sourced from off-shore windmills (Wind), or taken from the Dutch grid mix from 2021 (NL mix 2021); for the three impact categories assessed.

Table 8. Results for the LH PHS electricity scenarios for the three assessed impact categories and the relation between the electricity impacts and the infrastructure ones.

Category indicator	Scenario	LH PHS	N times bigger than infrastructure
GWP (kg CO2-eq/kWh)	Infrastructure	0.0095	-
	Wind	0.0327	2.4
	NL mix 2021	0.7439	77.2
WUDP (m3 water/kWh)	Infrastructure	0.0021	-
	Wind	0.0136	5.6
	NL mix 2021	0.0800	37.9
ADP-E (kg Sb-eq/kWh)	Infrastructure	4.802E-07	-
	Wind	1.338E-06	1.8
	NL mix 2021	1.341E-06	1.8

3.1.2.1 Contribution Analysis

Is relevant for this project to account for the environmental footprint of the infrastructure, but also to consider the total footprint, which also considers the electricity input. Moreover, it is important to see how are they related, how similar or different they are and which are the processes that contribute the most.

3.1.2.1.1 GWP

In Figure 26, the processes that contribute the most to GWP are depicted for the different electricity scenarios in the LH PHS plant. When the input of the LH PHS plant is sourced from wind power, the emissions from the electricity production increase significantly when compared with only the emissions from the infrastructure. Although this is not directly reflected in Figure 26, when looking at the Sankey diagram for this scenario (Figure 27), it is reflected that the infrastructure construction and maintenance reach 29% of all the emissions, whereas electricity demand to pump the water upstream the reservoir account for 71%. These emissions however are disaggregated in different processes which mainly account for the production of fixed and moving parts for offshore windmills. This is the reason why material production is still so relevant in this scenario, where granite production assumes a minor contribution whilst clinker, pig iron and nylon have a more relevant role. It also seems relevant to mention that 21.3% of all emissions in this scenario are inevitable emissions resulting from the efficiency of the plant, in other words, are the result of electricity losses.

In the case of using grid electricity to pump water upstream of the reservoir, the analysis gets simpler, as shown in Figure 26. The emissions from this scenario, which are 77 times bigger than the ones from infrastructure construction and maintenance, are 98.7% produced in electricity generation. As depicted in the Sankey diagram (Figure 28), coal and gas are the sources of these emissions and efficiency losses reach 29.6% of all CO2-eq emissions.

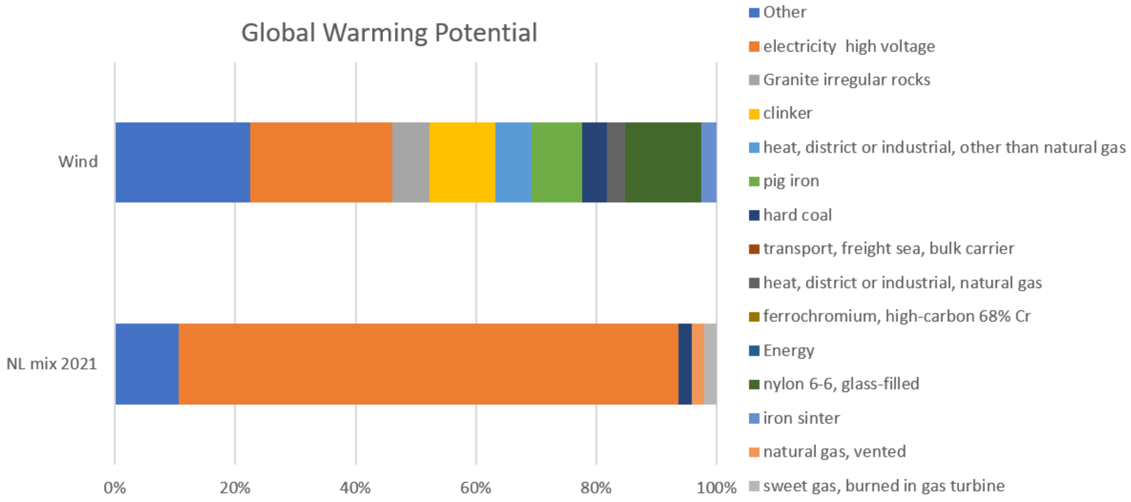


Figure 26. GWP contribution for the LH PHS alternative in the three electricity scenarios.

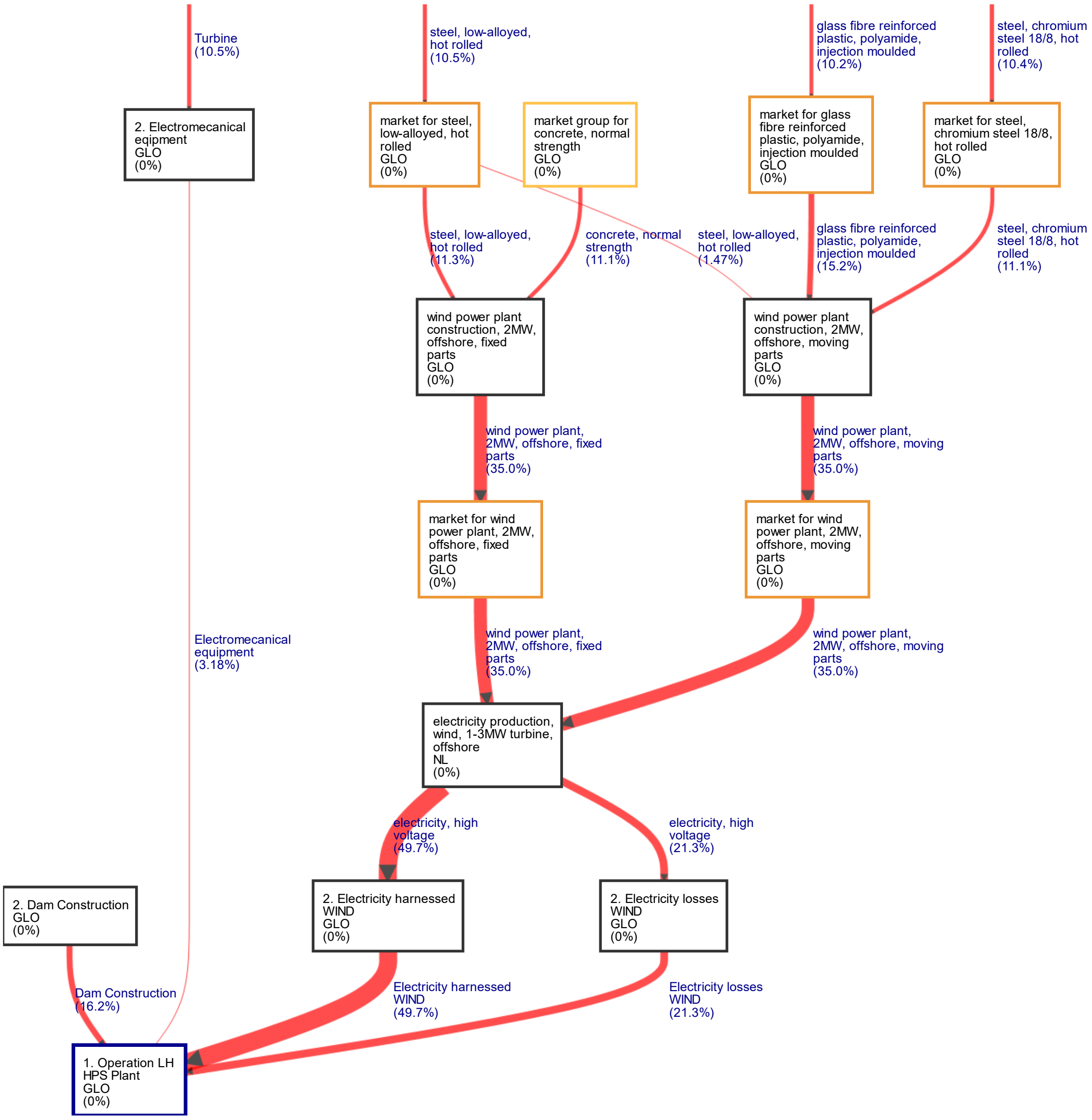


Figure 27. GWP Sankey diagram for the Wind scenario of the LH PHS plant.

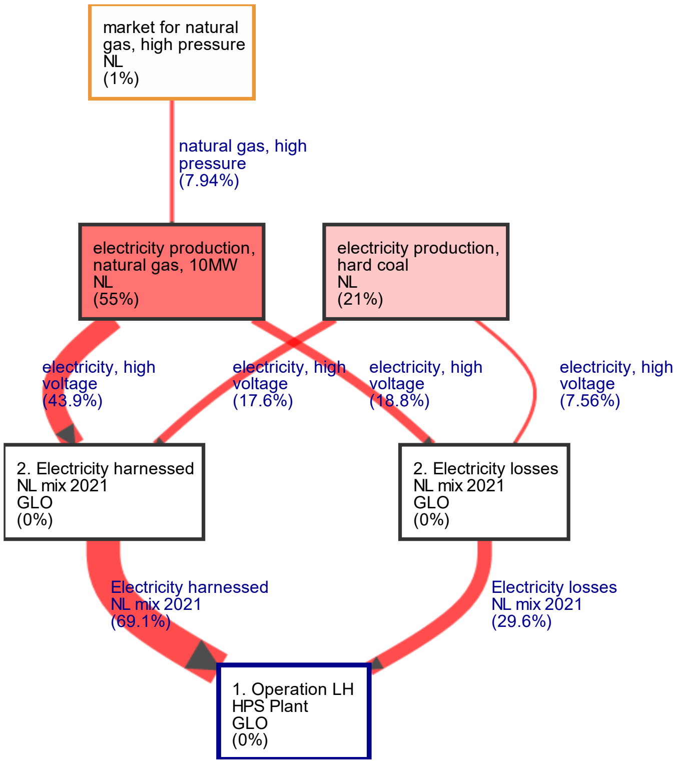


Figure 28. GWP Sankey diagram for the 2021 Dutch grid mix scenario of the LH PHS plant.

3.1.2.1.2 WUDP

Just as in the last section, WUDP contribution analysis for the different electricity scenarios of the LH PHS plant is shown in Figure 29. Looking at the big picture, it presents some similarities with the previous case where the infrastructure of the LH PHS plant has a minor role in the overall water consumption when compared to the water needs for electricity production. However, when looking in detail at where this water is needed, differences arise.

For the wind scenario, the breakdown of the chart presented in Figure 30 seems pretty similar to the one shown in the previous impact category. However, in this case, infrastructure construction and maintenance present just a bit more than 15% of the total water consumption. Again, the production of windmills is the major contributor in this scenario, where steel (in all its forms and alloys) and glass fibre production stand out as the most relevant processes in this category, representing 29.6% and 36.4% respectively. The main difference between these two materials is that while glass fibre is only used in the moving parts of the offshore windmills, steel is used in both the fixed and moving parts. Finally, efficiency losses in this process account for more than a quarter of all water consumption.

When using grid electricity, water use is almost 38 times higher than when only the infrastructure is considered, again, electricity production plays a major role. However, different to the previous case, coal and gas are not the only sources where this water consumption takes place. Nuclear (7.4%), hard coal (17.6%), solar-photovoltaic (24.4%) and natural gas (41.9%) are the four most relevant sources of water consumption in this scenario (Figure 31). It is striking to note that 24.4% of the water consumption has its origin in solar-photovoltaic electricity production, which represents 9% of the total grid mix used. Electricity losses reach almost 30% of all the water consumption in this scenario.

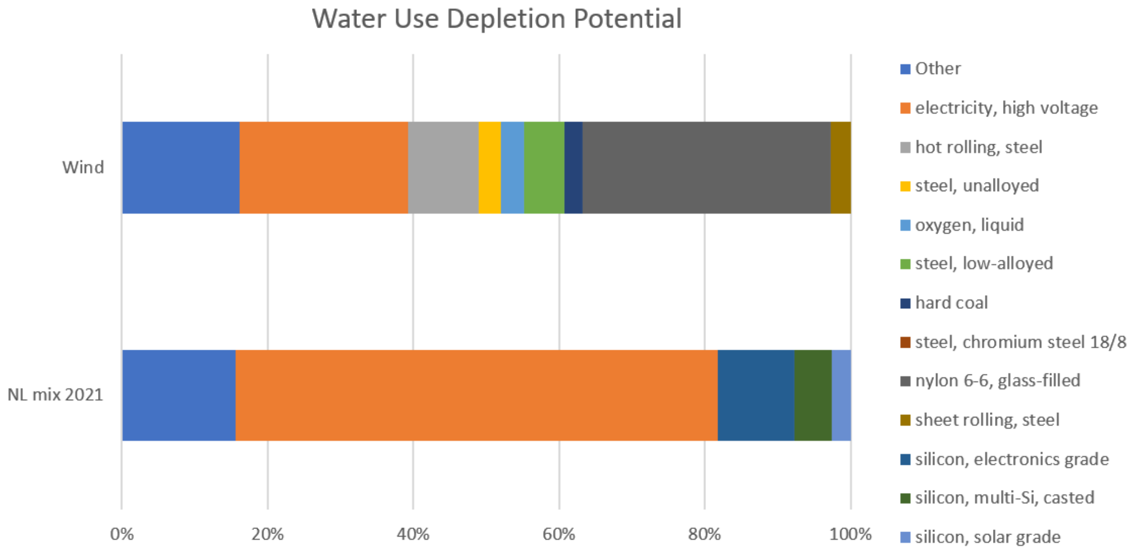


Figure 29. WUDP contribution for the LH PHS alternative in the three electricity scenarios.

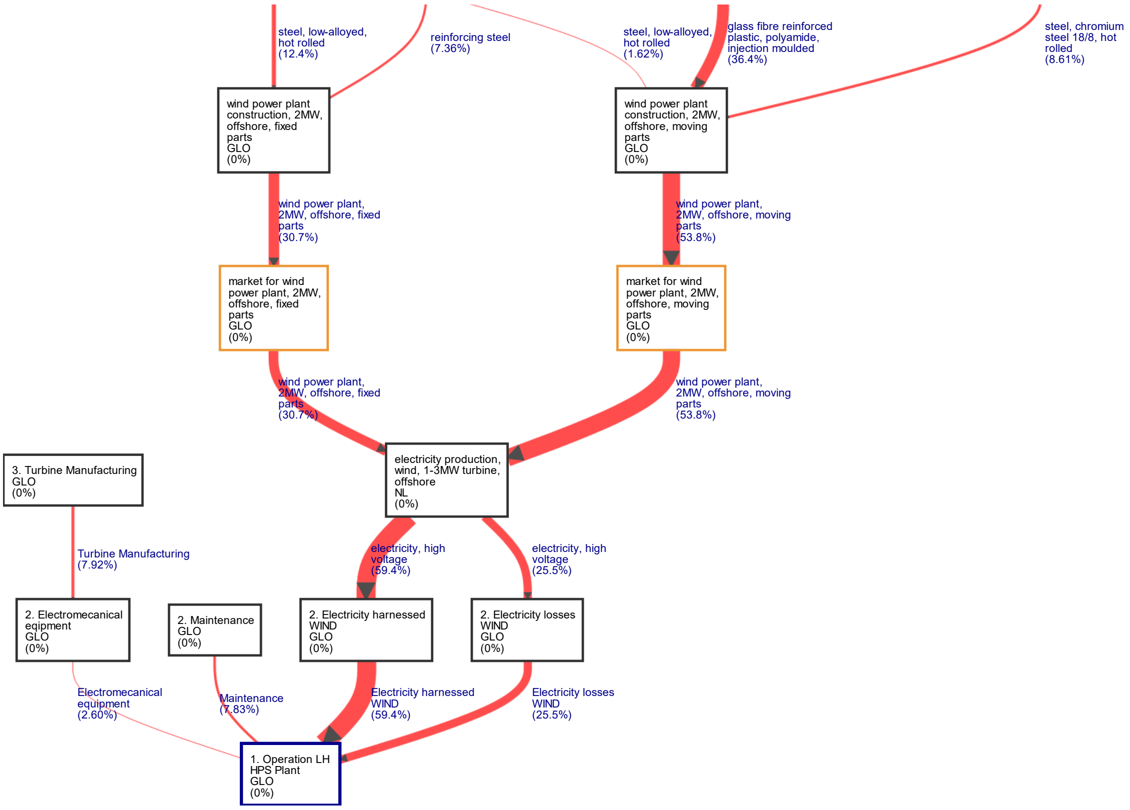


Figure 30. WUDP Sankey diagram for the Wind scenario of the LH PHS plant.

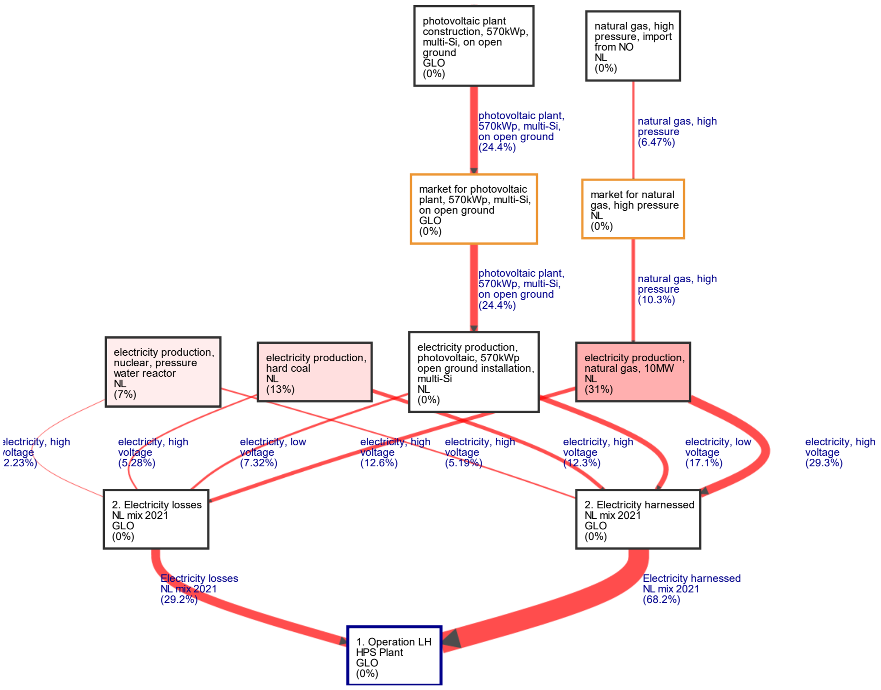


Figure 31. WUDP Sankey diagram for the 2021 Dutch grid mix scenario of the LH PHS plant.

3.1.2.1.3 ADP-E

Different to the previous impact categories, in this one, infrastructure still plays an important role, as it can be seen in Figure 32. In the wind scenario, electromechanical equipment from the LH PHS infrastructure still accounts for an important participation in the overall impact, with 35.2%. The same variety of metals as in the infrastructure calculations is used because the materials used in the production of windmills are similar to those in the LH PHS infrastructure: copper, lead and stainless steel. Nonetheless, the distribution of these metals in the windmills is different than in the LH PHS infrastructure, giving more importance to copper and not using gold. As can be seen in Figure 33, electricity losses in this case account for 19.2% of the total footprint in this scenario.

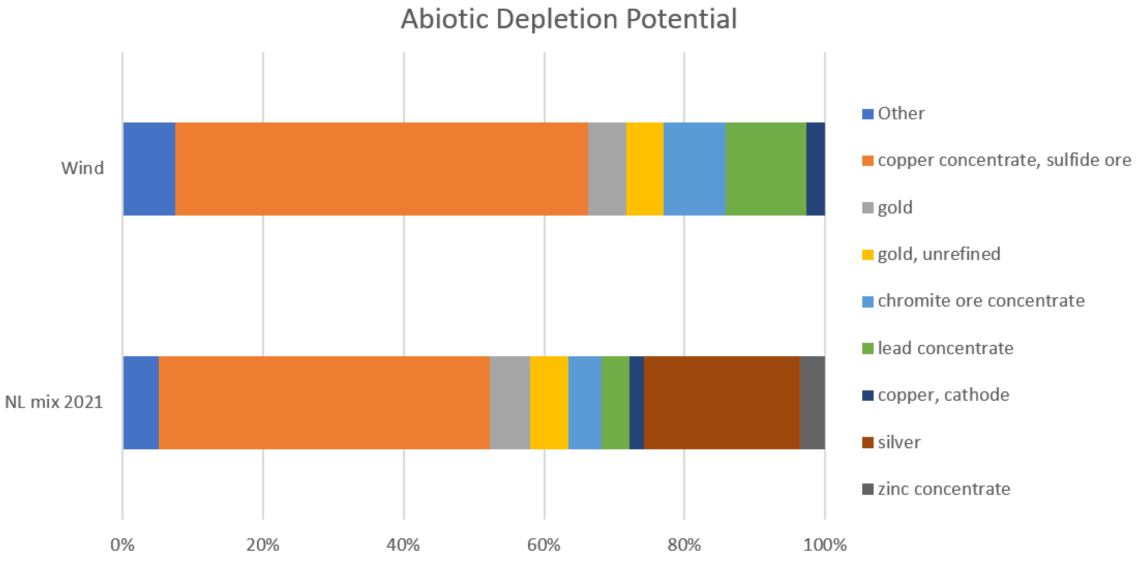


Figure 32. ADP-E contribution for the LH PHS alternative in the three electricity scenarios.

The abiotic depletion of elements when using the electricity of the 2021 Dutch grid mix does not differ much from an absolute point of view from the wind scenario. LH PHS infrastructure account for 35.1% of the total footprint in this scenario, as depicted in Figure 34. The rest of the emissions differ in the source and variety of metals, giving less relevance to offshore wind and much more to solar-photovoltaic electricity generation. This last process is where most of the impacts from the electricity generation come from, and where the introduction of different metals like silver and zinc play a major role. Electricity losses in this scenario account for 19.2% of the total footprint.

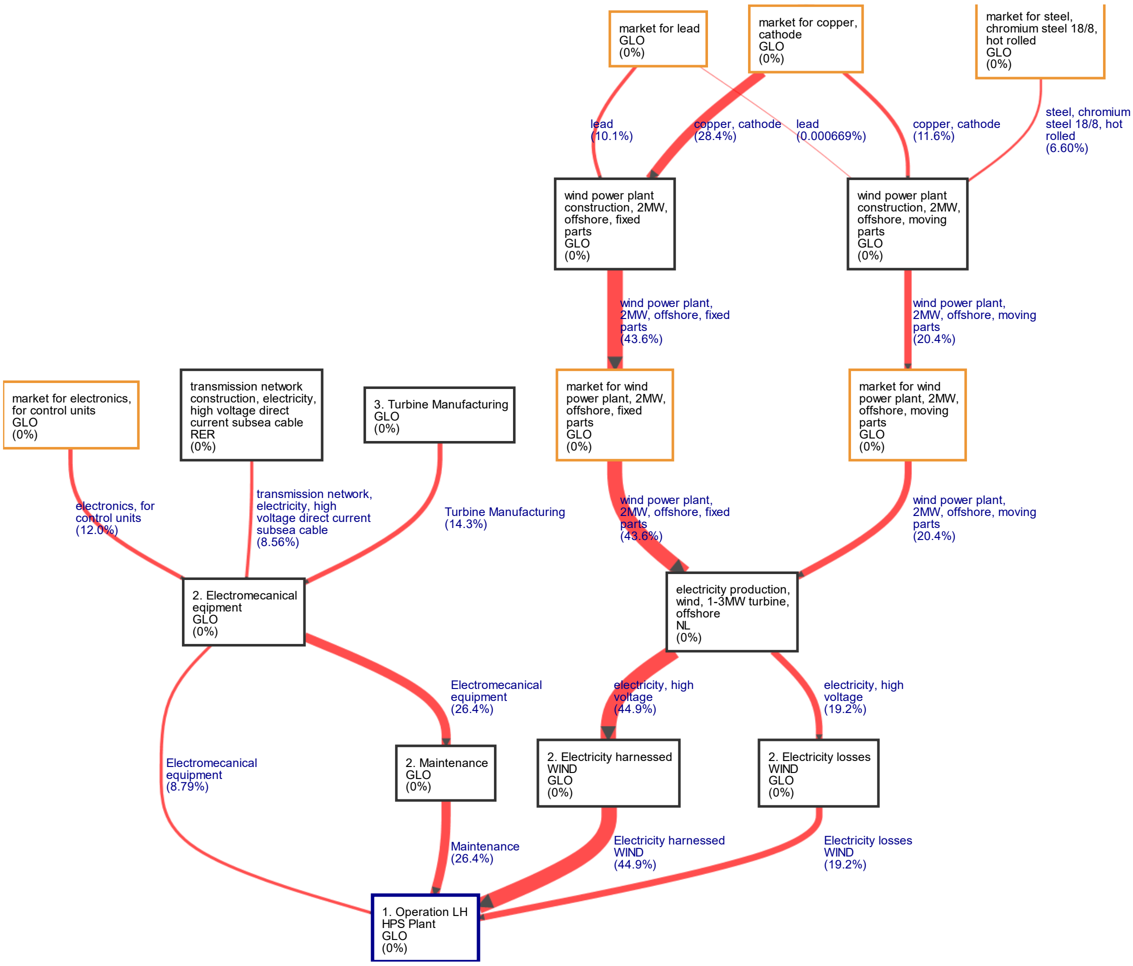


Figure 33. ADP-E Sankey diagram for the Wind scenario of the LH PHS plant.

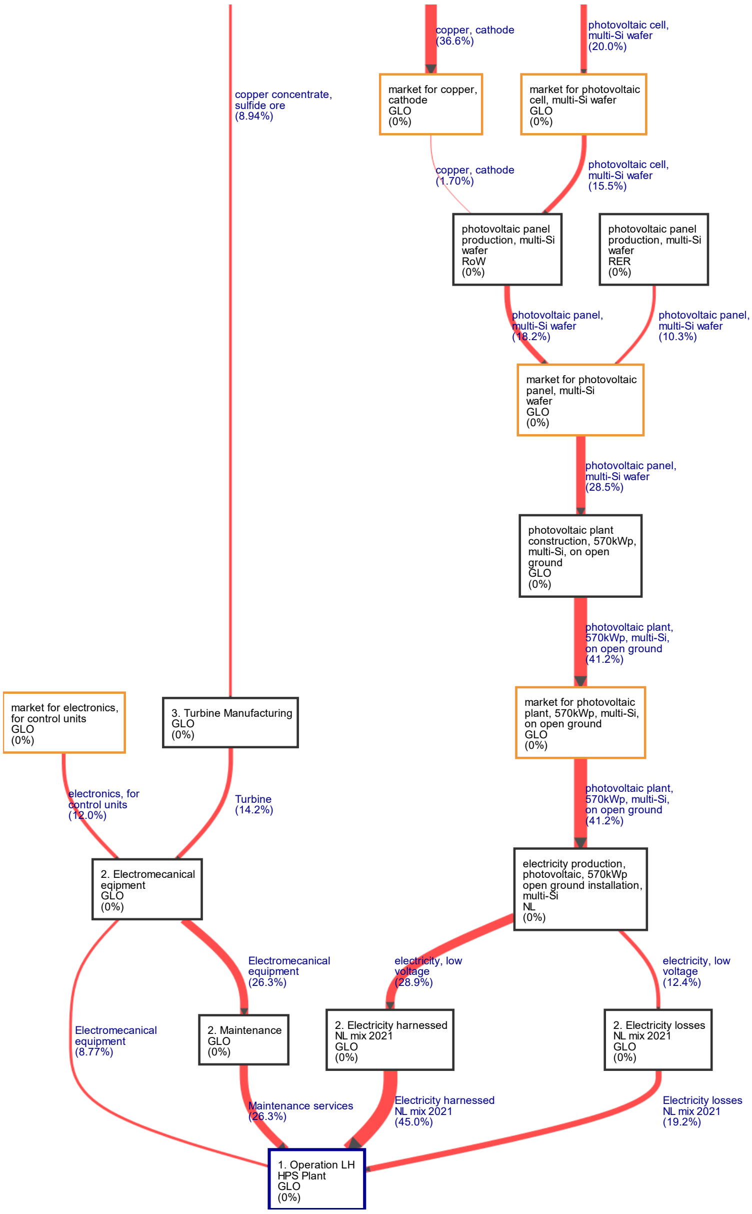


Figure 34. ADP-E Sankey diagram for the 2021 Dutch grid mix scenario of the LH PHS plant.

3.1.3 Comparison with other Storage Technology

In Figures 35-44, it can be seen the comparison between technologies and electricity sources. Moreover, due to the distortion between electricity source scenarios, a figure only for the Wind source is provided to see the results with higher resolution. These results are shown in a bar graph where the average value is presented and an error bar is used to represent the highest and lowest efficiency taken into account for each technology. At the same time, these results are shown in Table 10 for transparency purposes, where the values for the different efficiency scenarios and electricity sources for each category indicator are shown. Similarly, and with the same purposes, in Table 11, the emissions are divided by their origin, differentiating infrastructure, Energy Harnessed and Energy losses.

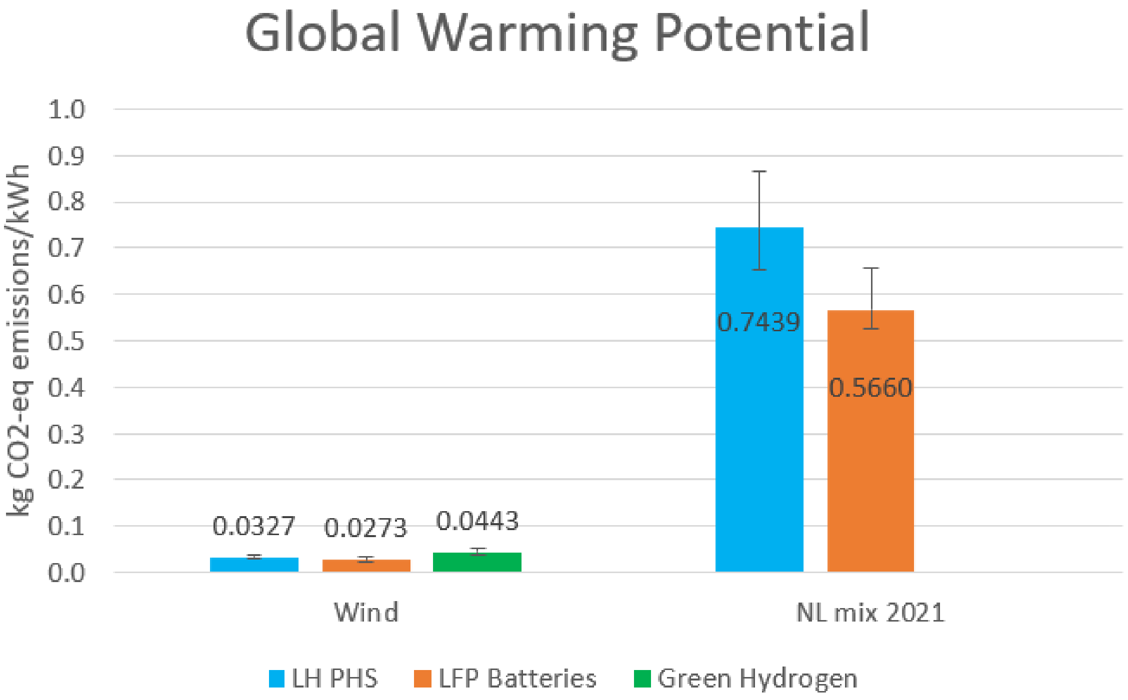


Figure 35. GWP results for the three technology alternatives in the two electricity scenarios.

The tendency shown in the last analysis remains with the different technologies, GWP and WUDP heavily increase with the utilisation of the 2021 Dutch electricity mix. ADP-E on the other hand, remains almost the same through the variation of electricity sources. The efficiencies changes do play an important role in all three indicators, varying their performance.

As previously stated, it is obvious when looking at the graphs, that the leading factor for CO2-eq emissions is the source of electricity, it is especially clear in Figures 37 and 38. Where the emissions are divided according to whether they originate from the infrastructure or from the energy needs (harvested and losses) and where LFP Batteries infrastructure represents a greater share of the total than for LH PHS. When looking at the technologies in the Wind scenario, the one that shows the best performance is LFP Batteries if the average or the best-case scenario is taken into account. LH PHS is the second best-performing technology, outperforming LFP Batteries only when these are in the worst-case scenario and LH PHS in the best one. Green Hydrogen is always outperformed, presenting the highest emissions in any efficiency scenario. Similarly, when looking at the Dutch mix scenario, LH PHS technology is outperformed by LFP Batteries almost in any case. The reasons why this happens are explained in in detail the contribution analysis section.

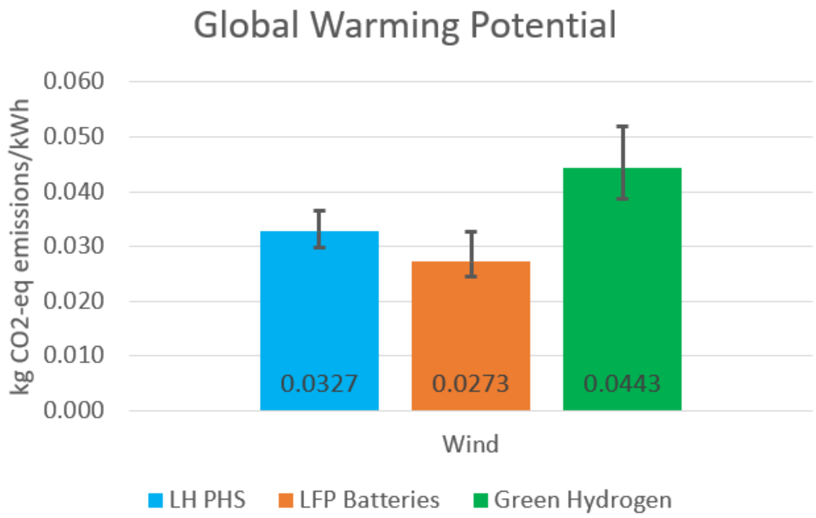


Figure 36. Detailed view of the GWP results for the three technology alternatives for the wind scenario.

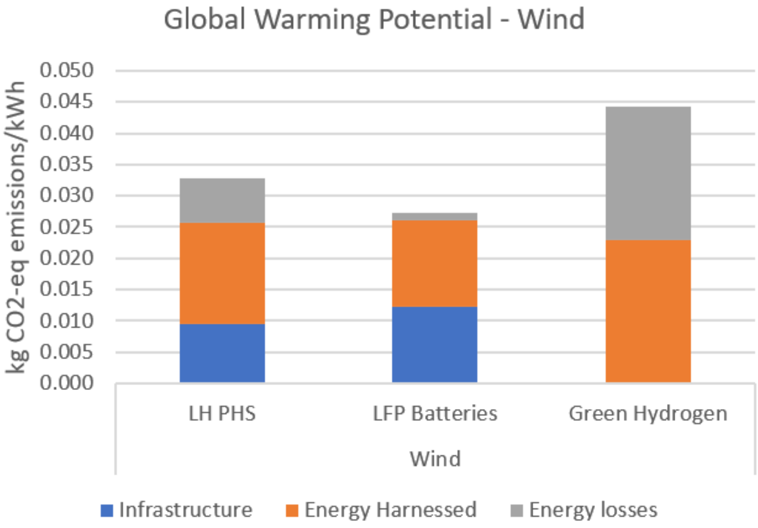


Figure 37. CO2-eq emissions per technology in the Wind scenario are differentiated in the infrastructure needs, Energy Harnessed and Energy losses.

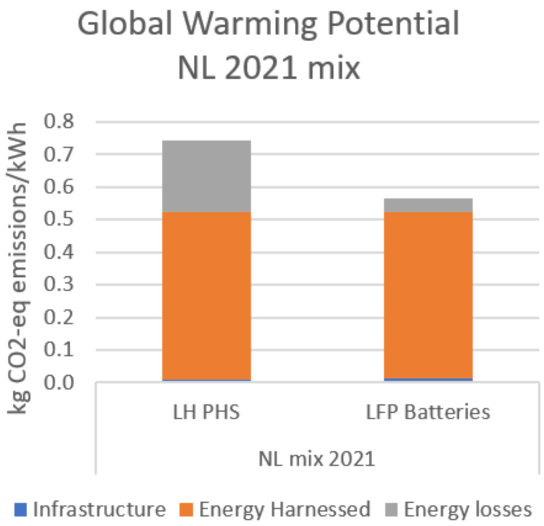


Figure 38. CO2-eq emissions per technology in the Dutch 2021 electricity mix scenario are differentiated in the infrastructure needs, Energy Harnessed and Energy losses.

For WUDP, again, the source of electricity remains the main factor driving water consumption regardless of the technology used, as depicted in Figures 41 and 42. And similarly to the previous category indicator, average emissions scale the same way for both the wind and Dutch mix; the best-performing technology is LFP batteries, followed by LH PHS and Green Hydrogen when considering the average values. The weight of the infrastructure in this case also follows the tendency of GWP, where LFP infrastructure has a bigger weight in proportion and in absolute than the infrastructure of LH PHS (Figures 39 and 40).

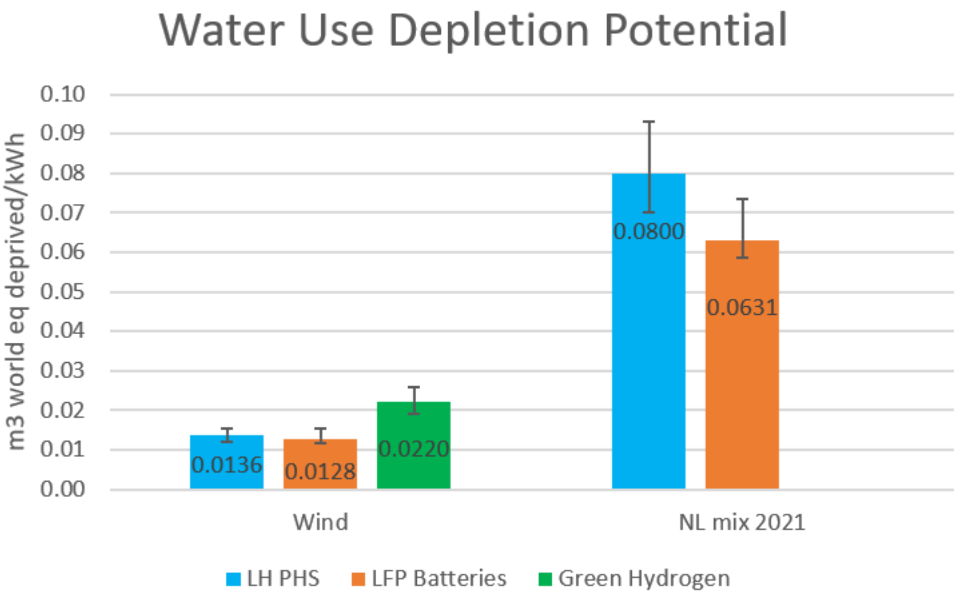


Figure 39. WUDP results for the three technology alternatives in the two electricity scenarios.

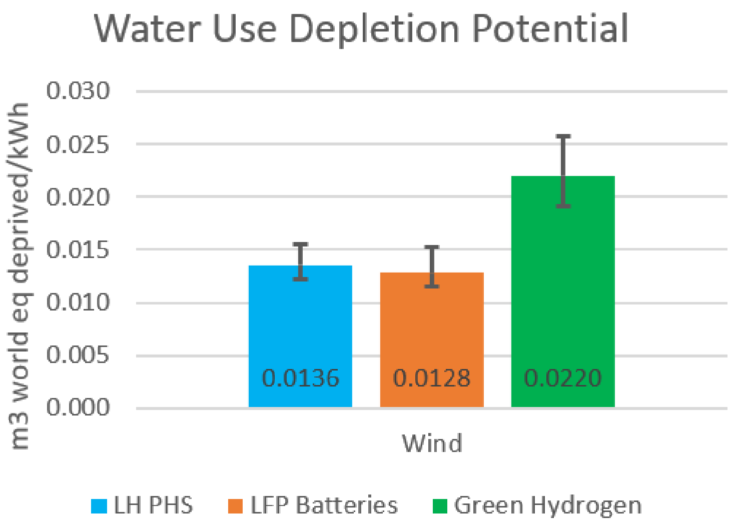


Figure 40. Detailed view of the WUDP results for the three technology alternatives for the wind scenario.

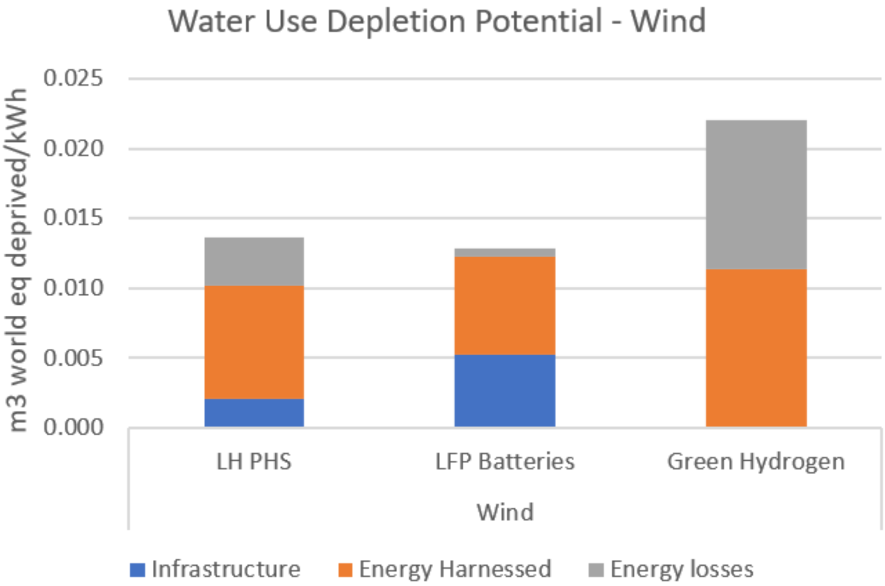


Figure 41. Emissions for WUDP per technology in the Wind scenario are differentiated in the infrastructure needs, Energy Harnessed and Energy losses.

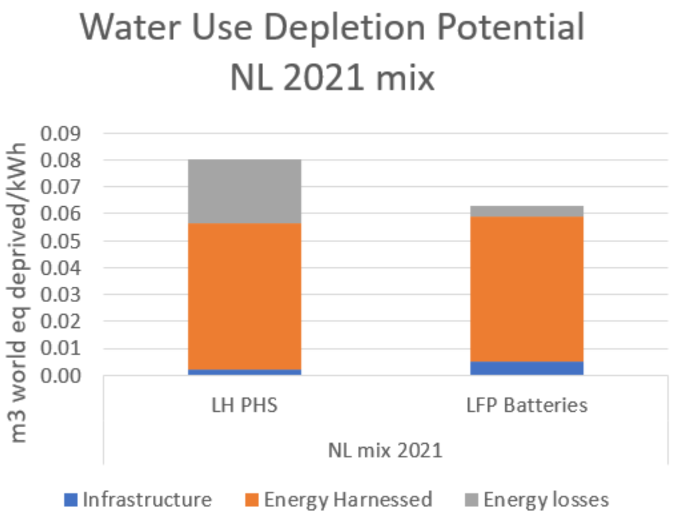


Figure 42. Emissions for WUDP per technology in the Dutch 2021 electricity mix scenario are differentiated in the Infrastructure needs, Energy Harnessed and Energy losses.

Results for the ADP-E are very different to the ones presented in the last two indicators (Figure 43). LFP Batteries present worse results than LH PHS and Green hydrogen, and the estimates for the two scenarios are very similar. Batteries' impact in this category, due to the lifetime variable (between 15-25 years) is directly affected by the number of batteries used. At the same time, seems important to remember that the hydrogen alternative is only taking into account the materials used for the production of electricity, no infrastructure is considered. This means that the results for the Green Hydrogen category are highly underestimated, even though Hydrogen is outperformed by LH PHS. Even in a higher proportion, the infrastructure for LFP Batteries here plays an important role in its contribution to the overall impact, whereas LH PHS proportion is important but not like in the LFP case (Figure 44).

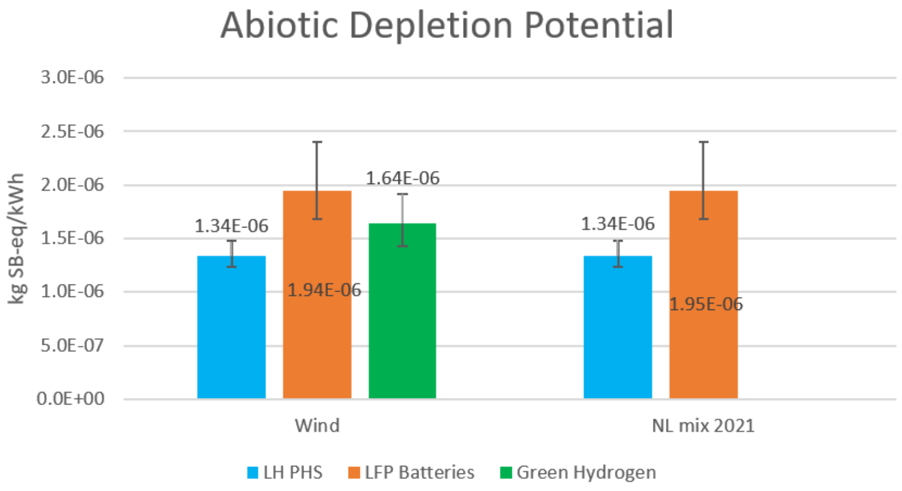


Figure 43. WUDP results for the three technology alternatives in the two electricity scenarios.

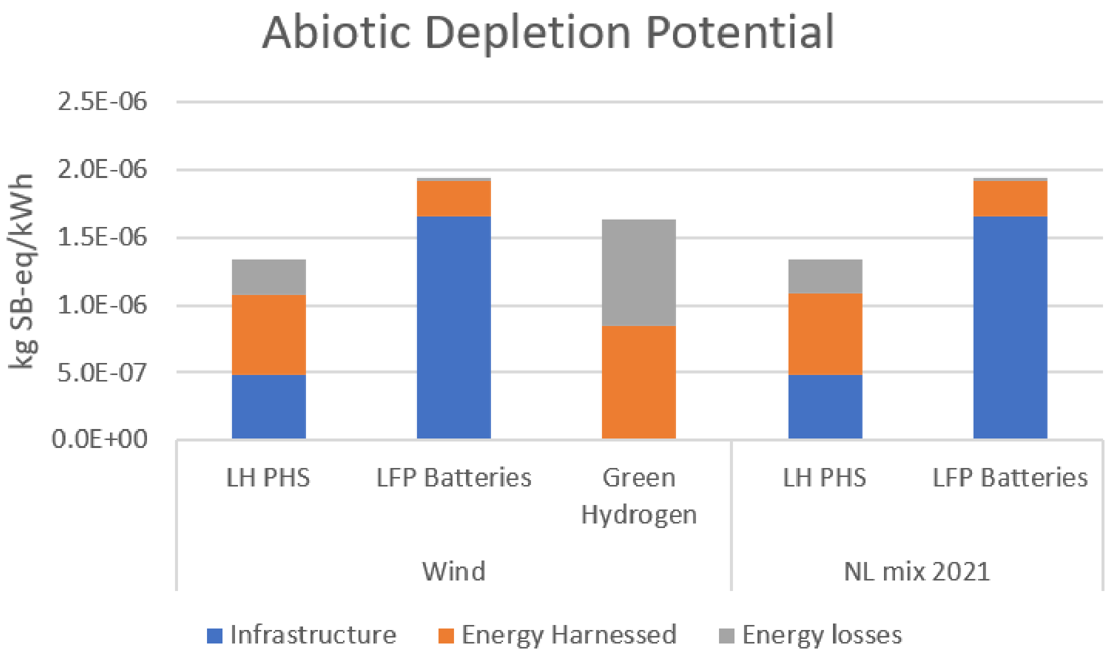


Figure 44. Emissions for ADP-E per technology in the Wind and Dutch grid scenario; differentiated in infrastructure needs, Energy Harnessed and Energy losses.

Beyond these results, BOM for LH PHS and LFP Batteries based on the calculations from the infrastructure are provided to give more intuitive results.

The results for LFP batteries are taken from the proxy from ecoinvent "battery cell production, Li-ion, LFP" used for the LCA model. From this process, it is detailed that for each kilogram of battery, 0.0755kg of aluminium, 0.178kg of graphite, 0.368kg of LFP (Lithium iron phosphate) and 0.139kg of copper are used. Depending on the lifetime considered the results for the material use vary. Results are depicted in Figure 45 and Table 9, where it can be seen that the use of Lithium iron phosphate can reach up to more than 140,000 tonnes. These numbers take into account the construction phase, but also the replacements needed for the proper storage of electricity for 100 years.

Table 9. Material requirements for the LFP Batteries alternatives in the different efficiency scenarios.

	Total material usage			
	Best case scenario	**Average**	**Worst case scenario**	
Battery cell, LFP	252	302	386	tonnes
Aluminium	19	23	29	tonnes
Graphite	45	54	69	tonnes
LFP	92	111	142	tonnes
Copper	35	42	54	tonnes

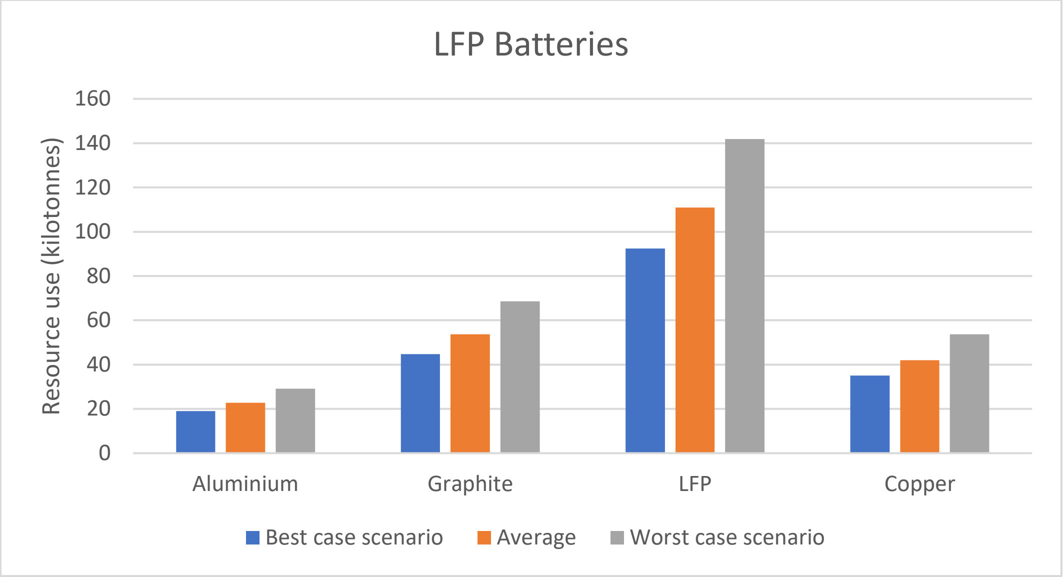


Figure 45. Comparative of the material requirements for the LFP Batteries alternative in its three efficiency scenarios.

The main difference between LH PHS and LFP batteries is the type of material used (results for LH PHS are shown in Table 6). Whereas LFP technology uses mainly metals, LH PHS uses also minerals like sand and concrete, which are employed in great amounts. However, batteries use Lithium, which is a metal that currently presents important challenges to overcome as it in environmental impacts regarding extraction and EoL management; and social and strategic areas such as human rights concerns and geopolitical dependencies (Alessia et al., 2021; Altiparmak, 2022; Gao et al., 2022; Petavratzi et al., 2022). On the other hand, it should also be mentioned that although concrete itself is not considered a scarce material, sand used for its production is (Torres et al., 2017, 2021).

Table 10. Summary table of the results for the technology alternatives, considering different efficiency scenarios and electricity sources for the three assessed impact categories.

Category indicator	Scenario	Scenario	LH PHS	LFP Batteries	Green Hydrogen
GWP (kg CO2-eq/kWh)	Wind	LOW efficiency	0.0366	0.0327	0.0363
		MID efficiency	0.0327	0.0273	0.0317
		TOP efficiency	0.0298	0.0245	0.0270
	NL mix 2021	LOW efficiency	0.8663	0.6550	-
		MID efficiency	0.7439	0.5660	-
		TOP efficiency	0.6521	0.5273	-
WUDP (m3 water/kWh)	Wind	LOW efficiency	0.0155	0.0153	0.0181
		MID efficiency	0.0136	0.0128	0.0157
		TOP efficiency	0.0122	0.0115	0.0134

	NL mix 2021	LOW efficiency	0.0930	0.0734	-
		MID efficiency	0.0800	0.0631	-
		TOP efficiency	0.0703	0.0585	-
ADP-E (kg Sb-eq/kWh)	Wind	LOW efficiency	1.48E-06	2.40E-06	1.34E-06
		MID efficiency	1.34E-06	1.94E-06	1.17E-06
		TOP efficiency	1.23E-06	1.68E-06	9.99E-07
	NL mix 2021	LOW efficiency	1.48E-06	2.41E-06	-
		MID efficiency	1.34E-06	1.95E-06	-
		TOP efficiency	1.23E-06	1.69E-06	-

Table 11. Summary table of the results for the technology alternatives and their division according to the origin of the emissions for the three assessed impact categories.

			Infrastructure	**Energy Harnessed**	**Energy losses**	**Total**
GWP (kg CO2-eq /kWh)	Wind	LH PHS	0.0095	0.0163	0.0070	0.0327
		LFP Batteries	0.0123	0.0138	0.0011	0.0273
		Green Hydrogen	0.0000	0.0228	0.0215	0.0443
	NL mix 2021	LH PHS	0.0095	0.5141	0.2203	0.7439
		LFP Batteries	0.0123	0.5116	0.0421	0.5660
		Green Hydrogen	0.0000	0.0000	0.0000	0
WUDP (m3 water /kWh)	Wind	LH PHS	0.0021	0.0081	0.0035	0.0136
		LFP Batteries	0.0052	0.0070	0.0006	0.0128
		Green Hydrogen	0.0000	0.0113	0.0107	0.0220
	NL mix 2021	LH PHS	0.0021	0.0546	0.0234	0.0800
		LFP Batteries	0.0052	0.0535	0.0044	0.0631
		Green Hydrogen	0	0	0	0.0000
ADP-E (kg Sb-eq /kWh)	Wind	LH PHS	4.802E-07	6.00532E-07	2.57371E-07	1.34E-06
		LFP Batteries	1.65E-06	2.69E-07	2.21E-08	1.94E-06
		Green Hydrogen	0	8.43179E-07	7.94062E-07	1.64E-06
	NL mix 2021	LH PHS	4.8019E-07	6.02397E-07	2.5817E-07	1.34E-06
		LFP Batteries	1.65233E-06	2.71E-07	2.23E-08	1.95E-06
		Green Hydrogen	0	0	0	0

3.1.3.1 Contribution Analysis

The contribution analysis of the different technologies is done without considering efficiency scenarios. This is mainly because efficiency differences may change slightly the weight electricity has, but not the overall picture of the technology. Thus, the efficiency baseline for each technology is used for this analysis. Results are presented with two visual representations, first a graph with the contribution of each technology and then a set of Sankey diagrams to identify the processes that contribute the most to each impact, tables with data are presented in Annex 1. The Sankey diagrams however, are only shown for LFP Batteries because those for LH PHS are already depicted in the last section for both electricity inputs from wind and the Dutch mix 2021 and, the Green Hydrogen model only takes into account the electricity inputs, which leaves no doubt for the source of the environmental damages. Nonetheless, it is considered important to highlight that even if the Batteries scenario is analysed, from all the infrastructure needed, this model only considers the batteries, and it does so with a proxy, making the results a rough approximation of reality. Moreover, since the Green Hydrogen model only take into account electricity consumption and efficiency, it does not make much sense to analyse anything else but the overall footprint. Thus, this alternative is not considered in this analysis.

3.1.3.1.1 GWP

The most relevant processes for the GWP category are listed in the graph presented in Figure 46. To avoid repetition but intend to build a section understandable by itself without having to go back to the previous findings, the analysis for LH PHS is a summarised version of what was written before, in the Electricity Scenarios part. This is repeated in the rest of the impact categories.

When using LH PHS technology sourcing its electricity from wind power, the infrastructure construction and maintenance reach 29% of all the emissions, whereas electricity demand accounts for 71%. These emissions however are disaggregated in different processes which mainly account for the production of fixed and moving parts for offshore windmills. This is the reason why material production is still so relevant in this scenario. It also seems relevant to mention that 21.3% of all emissions in this scenario are the result of electricity losses. In the case of using grid electricity GHG emissions are 98.7% produced in the electricity generation, with coal and gas as the sources of these emissions and electricity losses reaching 29.6% of all CO2-eq emissions.

This last analysis is identical to the scenario using LFP Batteries powered by the Dutch electricity mix. This is reflected in Figure 46, where the same processes have similar overall weight for the LH PHS and LFP technologies when electricity is sourced from the grid. The only difference is the proportions the harnessed and lost electricity have, the last one having much lower weight (7.43%) for the battery's scenario due to the higher efficiency they have. This difference in the losses is the reason why in the Dutch electricity mix scenarios, LFP Batteries outperform LH PHS technology, in the absolute values.

When wind power is used to provide electricity to the LFP batteries the picture does not change. Albeit the composition of the overall impact for LFP Batteries may be different than in the Dutch grid scenario, absolute values is still smaller than the emissions for an LH PHS plant. In Figures 47 and 48, it can be seen where the emissions for LFP Batteries originated. Providing the number of batteries needed for 100 years of operation (considering today's technology), contributes to roughly 35.4% of the total GHG emissions, while the electricity produced to store (ignoring the losses) accounts for 59.6%. This fact contrasts with the results from LH PHS in the wind scenario, where the infrastructure does not reach 20% of the overall GHG emissions but still presents a worse performance due to the lower efficiency.

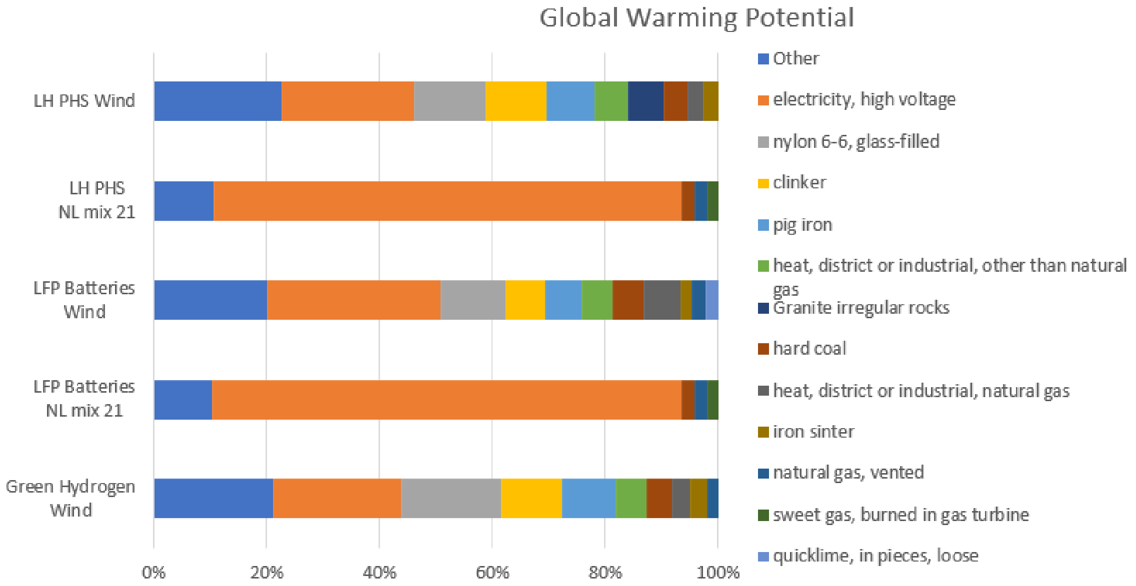


Figure 46. GWP contribution for all the technology alternatives in the electricity scenarios.

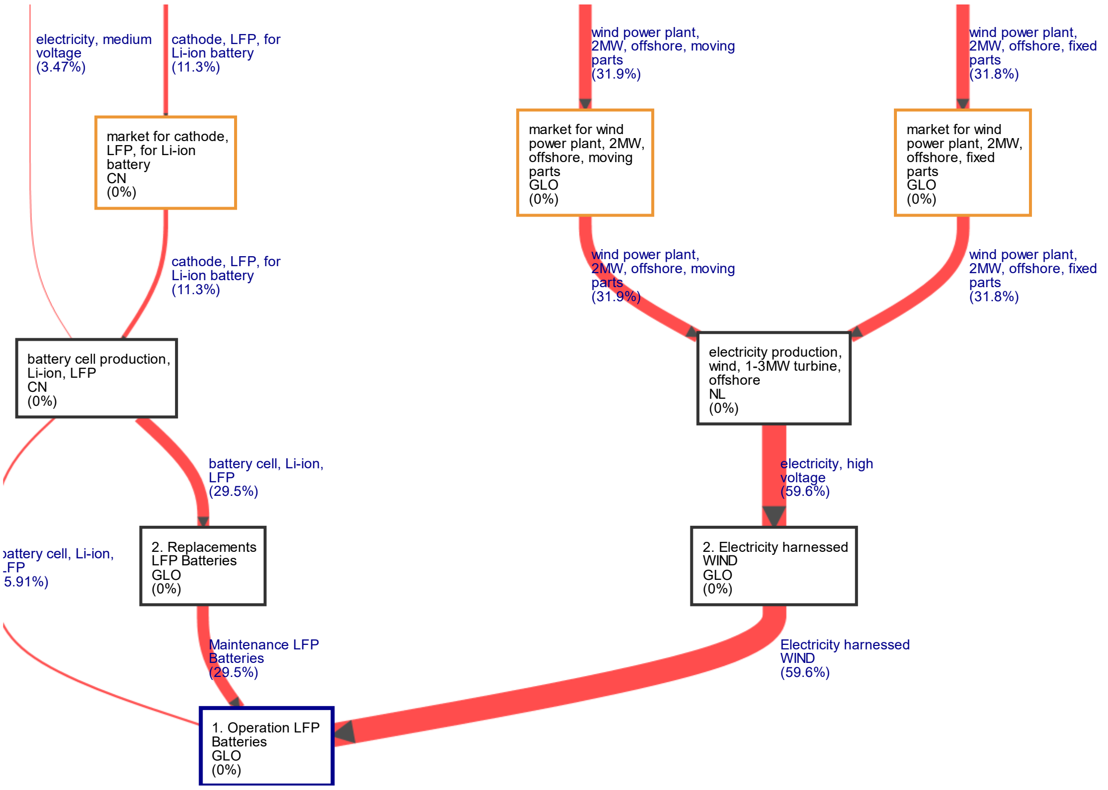


Figure 47. GWP Sankey diagram for the Wind scenario of the LFP Batteries.

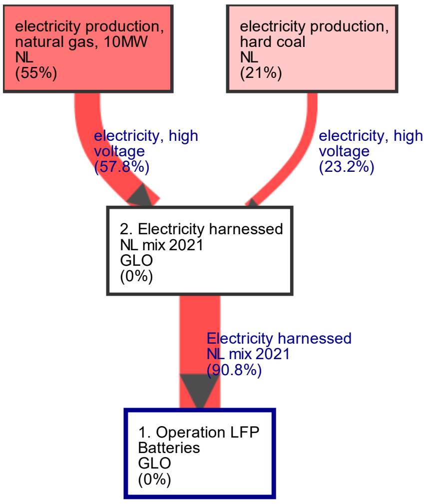


Figure 48. GWP Sankey diagram for the 2021 Dutch grid mix scenario of the LFP Batteries

3.1.3.1.2 WUDP

Results for WUDP are depicted in Figure 49. The water footprint for the infrastructure (construction and maintenance) for LH PHS technology in the wind scenario, accounts for slightly more than 15% of the total. From the electricity requirements, material needs for windmills are the major contributor in this scenario, where steel and glass fibre production stand out as the most relevant processes in this category, representing 29.6% and 36.4% respectively. Efficiency losses in this scenario account for more than a quarter of all water consumption. When using electricity from the grid, nuclear, hard coal, solar-photovoltaic and natural gas are the four most relevant sources of water consumption in this scenario. Electricity losses are responsible for nearly 30% of all water consumption.

When considering the LFP batteries scenarios, the picture is similar to the one in GWP in the sense that the infrastructure needs have a more relevant role than in the LH PHS scenarios. At the same time when wind power is used as input, there are more or less the same number of processes as when this same source of electricity powers LH PHS technology. Water consumption from batteries infrastructure (construction and replacements) accounts for 31.7% of the total footprint. Whereas electricity use (without considering losses) is responsible for 63.1% (Figure 50). When the electricity grid is used for powering LFP batteries, the weight of their material needs footprint is reduced, not even being displayed in the Sankey diagram in Figure 51, whereas harnessed electricity reaches 86.5%. Similarly, to the LH PHS scenario when powered by the Dutch grid, the sources that gather the major impacts are natural gas, solar-photovoltaic and hard coal with a participation of 37.1%, 21.7% and 15.6% respectively. Electricity losses for the wind scenario are responsible for 4.5% of the water use, whereas, in the Dutch grid scenario, losses go up to 7% of the total water footprint.

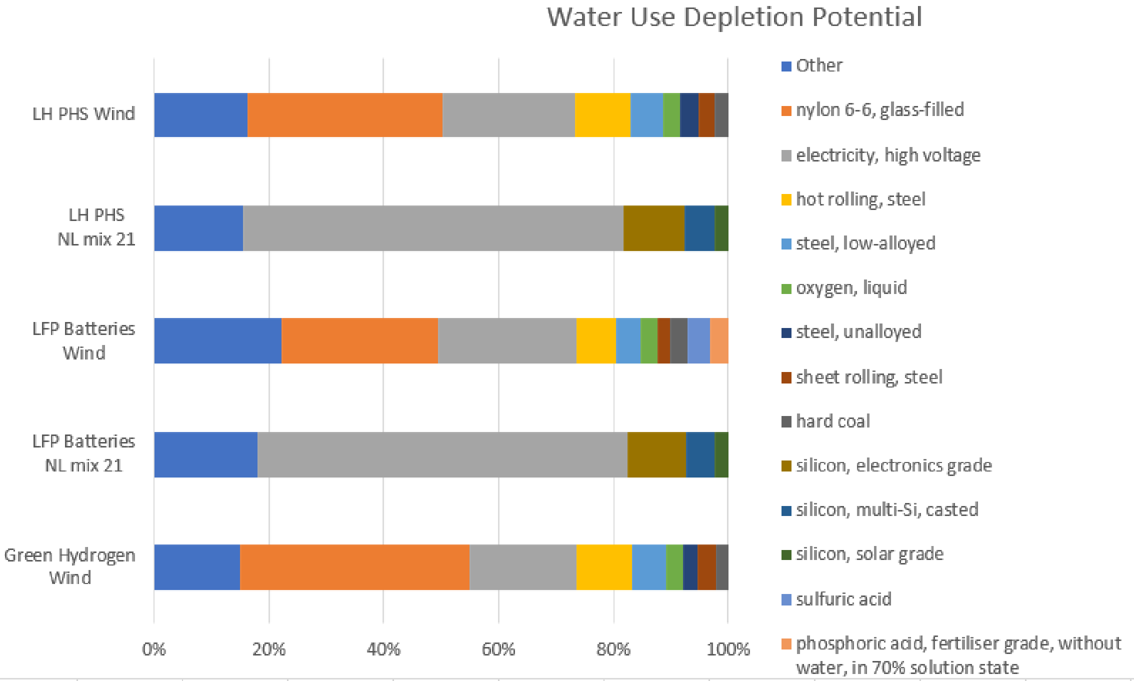


Figure 49. WUDP contribution for all the technology alternatives in the electricity scenarios.

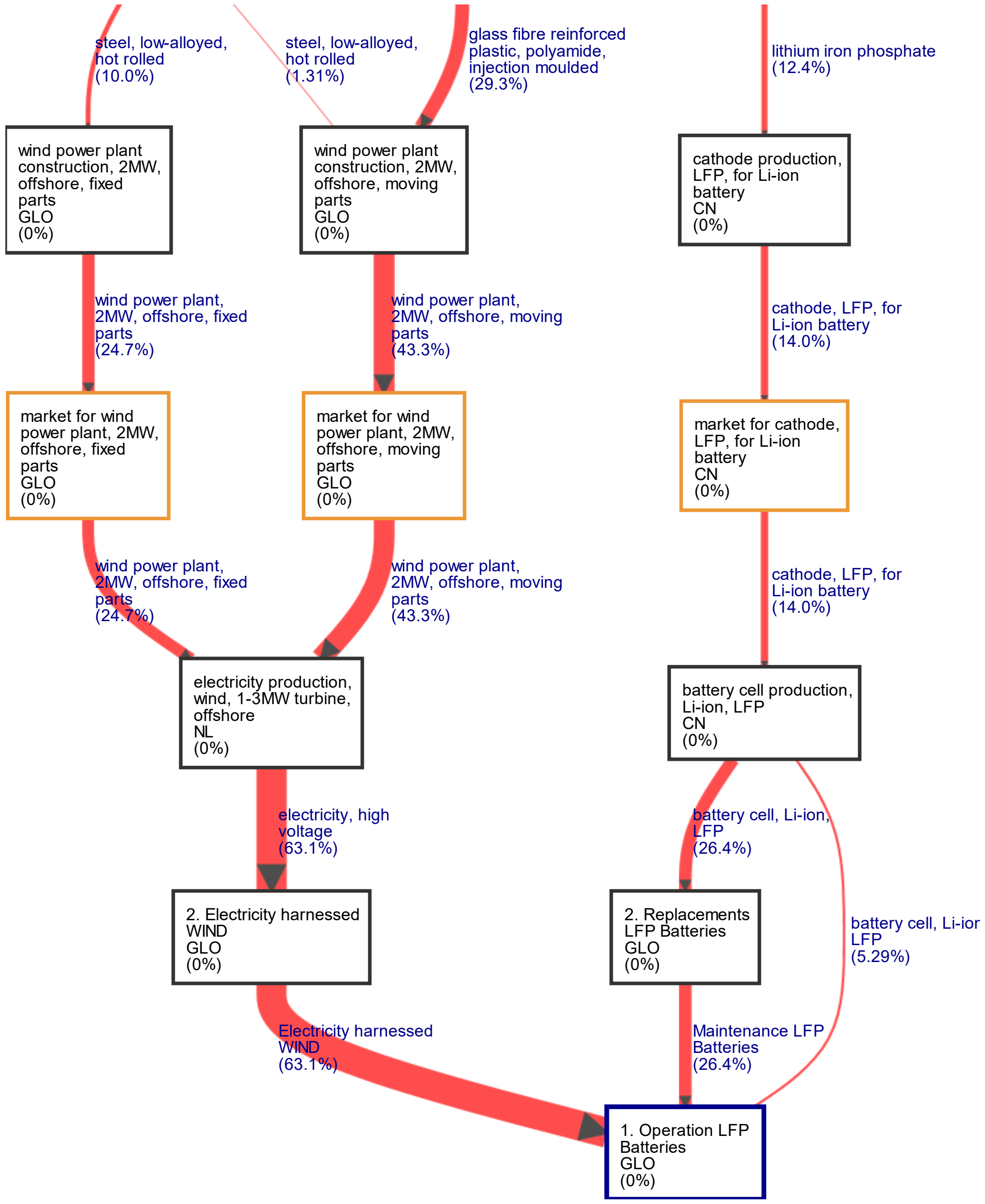


Figure 50. WUDP Sankey diagram for the Wind scenario of the LFP Batteries.

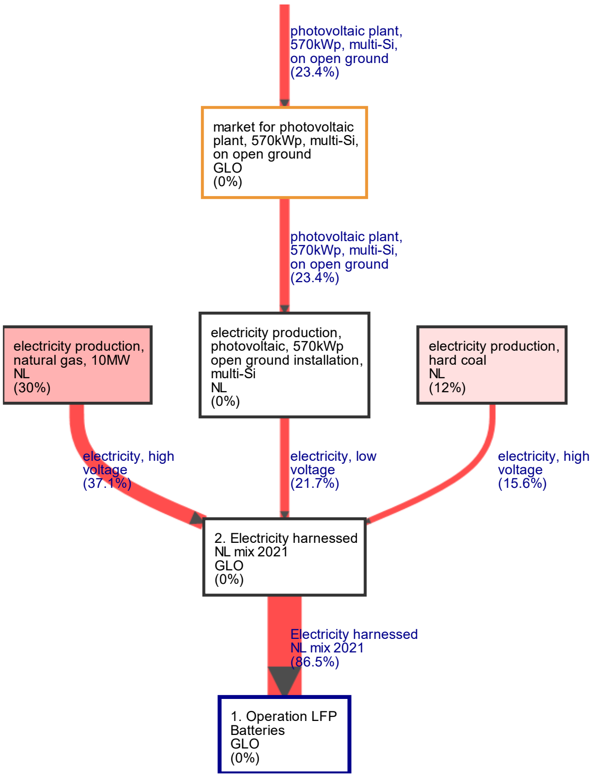


Figure 51. WUDP Sankey diagram for the 2021 Dutch grid mix scenario of the LFP Batteries.

3.1.3.1.3 ADP-E

When ADP-E are considered in the LH PHS case, electromechanical equipment accounts for important participation in the overall impact, with 35.9%. The composition of the elements used in the infrastructure is very close to the one used for offshore wind electricity generation. Nonetheless, in windmills, copper has a bigger role than gold, which is used for electronics in the LH PHS plant, as shown in Figure 52. The abiotic depletion of elements when using the electricity of the 2021 Dutch grid mix does not differ much from an absolute point of view from the wind scenario. The emissions differ in the source and variety of metals, giving less relevance to offshore wind and much more to solar-photovoltaic electricity generation. This last process is where most of the impacts from the electricity generation come from, and where the introduction of different metals like silver and zinc plays a major role. Electricity losses for this technology account for 19.2% of the total footprint regardless the of source of electricity.

Sources of electricity inputs have a lighter role in Abiotic Depletion Potential when compared with GWP and WUDP, for the LFP batteries alternative. This means that infrastructure construction and replacements are the determining factors in this impact category. When looking at the Sankey diagrams (Figures 53 and 54) the same processes repeat for both alternatives giving battery production the major responsibility of this category, reaching around 66.5% for both scenarios. Moreover, copper alone reaches 83.5% and 77.4% for wind and grid scenarios respectively.

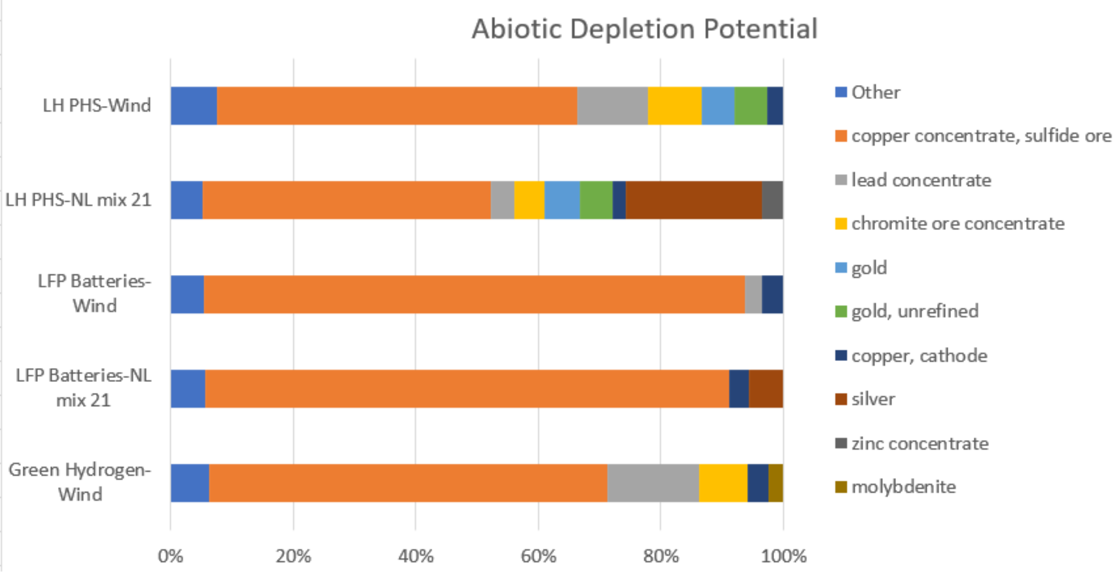


Figure 52. ADP-E contribution for all the technology alternatives in the electricity scenarios.

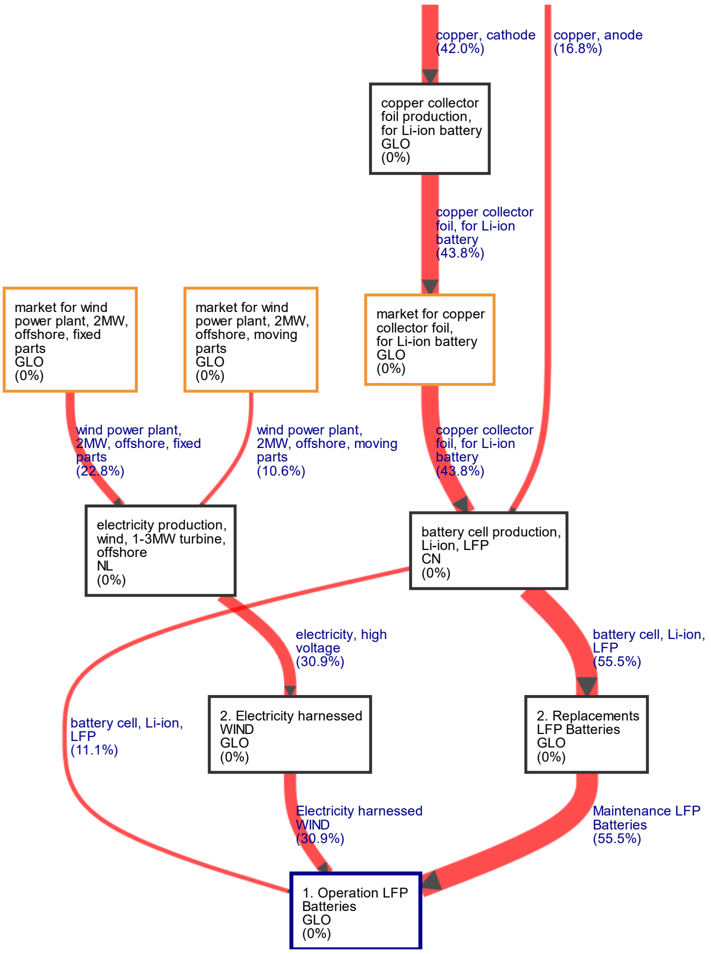


Figure 53. ADP-E Sankey diagram for the Wind scenario of the LFP Batteries.

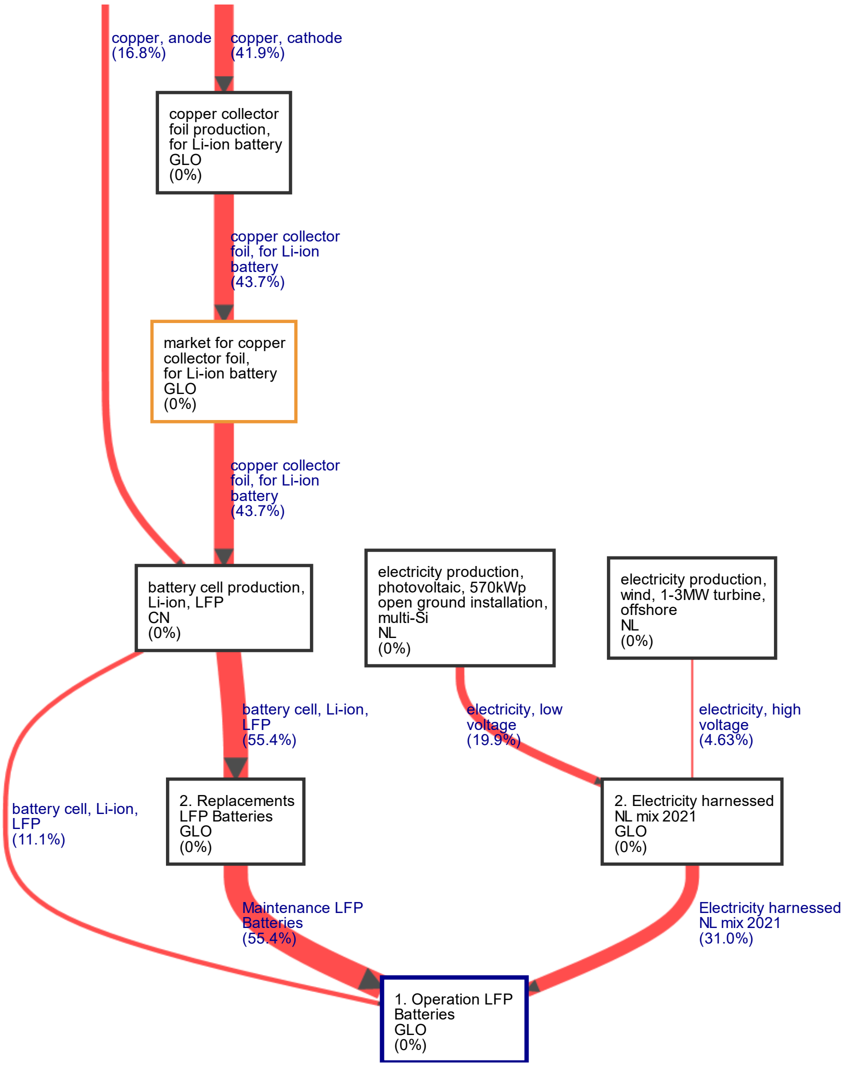


Figure 54. ADP-E Sankey diagram for the 2021 Dutch grid mix scenario of the LFP Batteries.

3.2 Economic flows not followed to the system boundary

To avoid data gaps, ecoinvent database is used, which takes into account all the supply chain needs and emissions. However, for the LH PHS plant, waste from the manufacturing stage and decommissioning of the plant has been considered out of the scope of this study. LFP li-ion battery impacts are approximated using a proxy for the batteries and the electricity use. The rest of the infrastructure needed like HVAC systems, construction of the building or electric infrastructure are ignored. In the same line, for the Green Hydrogen alternative only the electricity needs are considered; all the infrastructure is not considered due to the complexity of the estimations required and the time restrictions of this study.

3.3 Consistency check

Different characteristics are compared between the alternatives to check the consistency of the results. These characteristics with their respective comparison are listed and described below.

- **Data sources:** The knowledge and the data to chose the materials and works needed for the model come from the Alpheus project. However, to build the model, most of the data has been sourced from ecoinvent 3.9 (Wernet et al., 2016). Some exceptions are extracted from LCA studies from the literature for the LH PHS alternative, examples of this are the ship emissions and the granite emissions.
- **Data accuracy:** As mentioned already, all the data used comes from validated scientific literature or databases. Thus, there might be a difference between the accuracy of these two sources of data. Furthermore, when considering the three technology alternatives, they are not researched at the same depth. LH PHS processes are extensively detailed regarding the infrastructure, whereas proxies are used to model LFP Batteries equipment and only electricity inputs and their efficiencies in green hydrogen processes are used for this last alternative.
- **Technology coverage:** The maturity of the three technologies is not the same. All the data is indeed sourced from literature or studies from the research group that is developing the technology (as is the case for the LH PHS), however, this technology is still in the developing stages. This case is similar to Green Hydrogen in that, although the technology exists already, it has never been deployed at this scale. Moreover, only electricity needs have been modelled due to a lack of matching processes with this technology in ecoinvent. On the other hand, there are the LFP Batteries that, although they are a semi-mature technology, there are still many improvements to be made, for example, the increase in life cycles.
- **Data age:** Not all processes have been checked to review their age, however, the processes forming the electricity mix from the Netherlands have. This is done because of the major importance these processes have in the overall results. The findings are that in ecoinvent, most of the electricity data is from 2012, however, there are three exceptions from the electricity generation sources. Heat and power co-generation from biogas, that no date is mentioned; oil, with 2007 as the year when the data is gathered and; natural gas, with the data collected around the mid-1990s. This last fact about the gas emissions may result as a weak point of this analysis since they are an important part of the final GHG emissions and technology most likely has evolved, reducing their environmental impact. However, these emissions are the product of a chemical reaction, which technology, may have

reduced, but it is not believed that these emissions would see a great change with the update of data.

- **Geographical coverage:** Many processes are forming the different alternatives located mainly in European countries/areas, but since not all processes are covered in these areas, some processes are located elsewhere globally. However, as an important highlight, electricity used in the last stage "Operation" for the three alternatives, is always sourced from the Dutch market, either wind or the grid mix.

3.4 Completeness check

Following ISO 14044 indications a completeness check is performed to ensure that all relevant data needed to understand and have a correct interpretation of the results is provided (ISO, 2006).

The results obtained are compared with the results from other studies found in the literature. However, LH PHS has not been studied before from an LCA perspective. Thus, for LH PHS the comparisons have been made with studies that consider Hydropower of different sorts. On the other hand, for LFP batteries and Green Hydrogen, studies have been found that consider these technologies and are researched with further detail than in this report, which makes them an ideal starting point to compare.

3.4.1 LH PHS

The literature review on LCA for Hydropower technology from Gemechu and Kumar (2022) is used for this comparison. From the studies they took into account, only those with hydro plants with the same or bigger installed capacity as the one studied in this report (2000MW) and with similar scope (Cradle-to-gate) are considered. Unfortunately, most of these studies only consider GHG emissions, which is the only category indicator used to compare results. These studies are listed in Table 12.

When looking at the emissions of these different studies, it is clear that there is no consensus on one number, although they all are around the same close range of values. For the LH PHS considered in this study, when only considering the infrastructure needed (considering all its lifecycle), GHG emissions reach 9.5g of CO2-eq/kWh. This number matches the emissions considered in other hydro projects. This means that the proposed LH PHS project has a similar performance as the already established big-scale hydro projects.

None of the studies shown in Table 12 has a contribution analysis itemized in a way that makes it possible to build a comparison between their results and those shown in this report. Thus, it is not possible to assess if the distribution of the emissions in this study is similar or not to those in traditional PHS projects.

Table 12 Characteristics from similar (in scale) Hydro projects with their original sources. Summarised table from Gemechu and Kumar (2022)

Project type	Installed capacity (MW)	Scope	GHG emissions (g CO2-eq/kWh)	Source
Reservoir	14.000	Cradle-to-grave	5.27	(Ribeiro & Da Silva, 2010)
Reservoir	1.499	Cradle-to-grave	15.2	(Siddiqui & Dincer, 2017)
Reservoir - concrete gravity dams - earth-rockfill dams	5.850	Cradle-to-grave (no reservoir emissions)	11.11 8.36	(J. Zhang & Xu, 2015)
Reservoir	12.600 6.400	Cradle-to-grave	7.6 +-1.09 9.1 +-1.36	(Z. Li et al., 2017)

3.4.2 LFP Batteries

Similarly to LH PHS technologies, a literature review on LCA of batteries is used for comparing the results obtained in this study with other published work. In this case, the work from Peter et al. (2017) is used and their results are shown in Figure 55. Moreover a more recent LCA on Batteries from Xu et al. (2022) is also used to give a broader view. This second reference in Figure 56 is not as direct as the one from Peter et al. (2017). Considering the Base scenario in 2020 and the manufacturing happening in China, it concludes that the emissions per kWh of capacity of the battery are 68kg of CO2-eq. However, it is considered that these emissions are for the whole lifetime of the battery, for which it needs to be translated into the same unit as the ones used in this report. For this it is divided the emissions by the times that the battery is charged and discharged for the whole lifetime. Assuming that the battery is charged and discharged once a day and that it has 20 years of

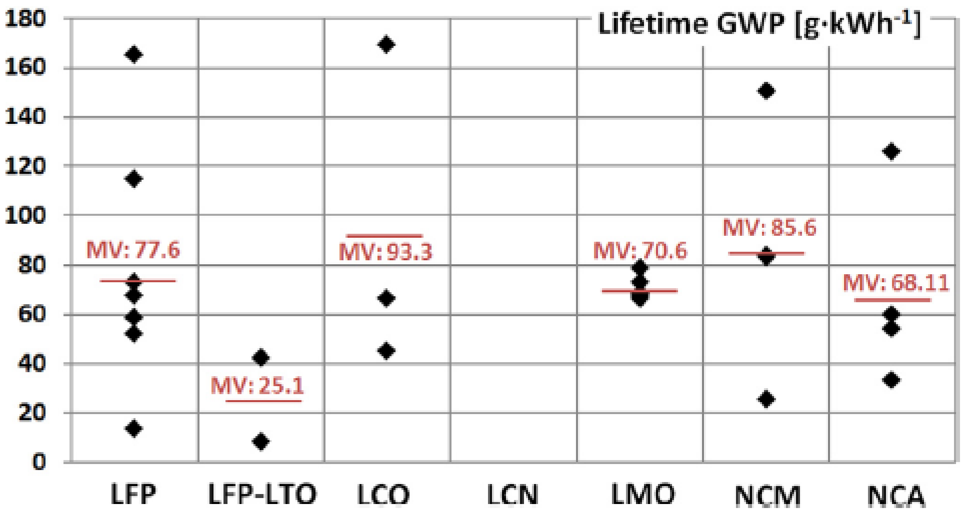


Figure 55. GHG emissions from different types of batteries (Peters et al., 2017).

lifespan, the 68kg of CO2 equivalent have to be divided by 7,300 cycles; which gives a result of 9.3g of CO2-eq/kWh.

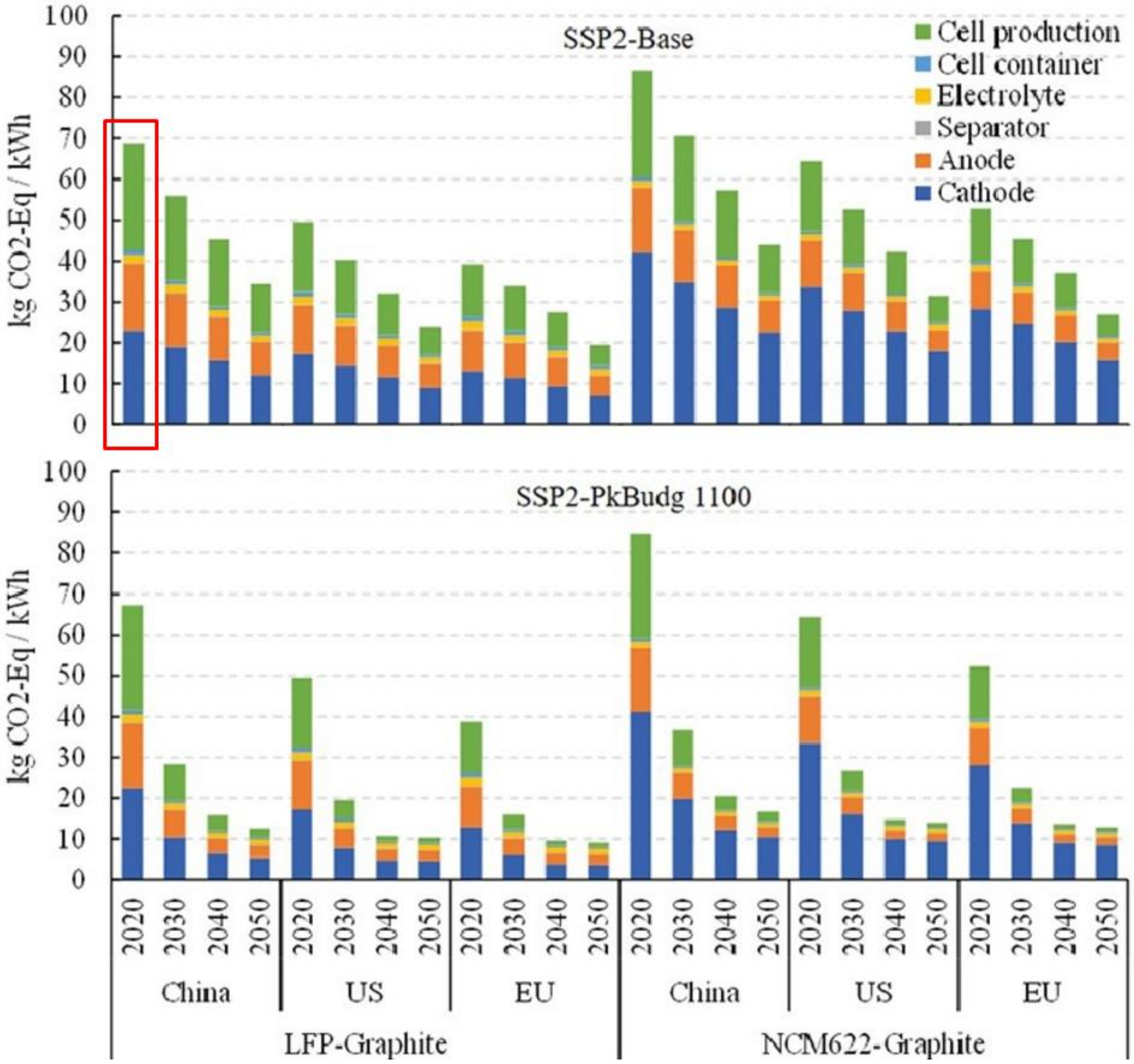


Figure 56. GHG emissions from different types of batteries, time and manufacturing origin (Xu et al., 2022)

Another remark is the fact that previous results for LFP Batteries always consider electricity input, either from wind power or from the grid. However, to provide a 'fair' comparison, a simulation for LFP batteries ignoring electricity inputs are run. This means that the only input for this analysis has been the amount of kg of batteries used as a proxy, with results showing that 25g of CO2-eq/kWh is emitted. These results are between those from Peters et al. (2017) and the ones from Xu et al. (2022). This leads to the belief that the results from the proxy used for battery estimations are an acceptable average of the impacts of storing electricity with LFP batteries.

3.4.3 Green Hydrogen

The model used for Green Hydrogen is different from those for LH PHS and LFP Batteries in the sense that no infrastructure is modelled. To assess the impact that the infrastructure may have and the differences between the model used in this report and reality, the results obtained in this study are compared with a study where electricity is produced from green Hydrogen made from wind (Ozawa et al., 2019). In this study the production of electricity is based in a mono-firing plant for Hydrogen and the whole supply chain for hydrogen is taken into consideration (Figure 57). This study is based on the assumption that hydrogen is produced in Australia or Norway from wind electricity and is transported to Japan to produce electricity. From these assumptions, two values are obtained for GWP: 72 and 89g CO2-eq/kWh. This shows a big difference when compared with the results obtained in this study, where Hydrogen emits 44.3g CO2-eq/kWh. This study also considers the GHG footprint for green hydrogen sourced from solar electricity and it estimates it at 198 and 203g/kWh depending on the country of production.

Considering the omission of infrastructure in this study this difference of values does not seem surprising, although they are very relevant for the proper comprehension of the results.

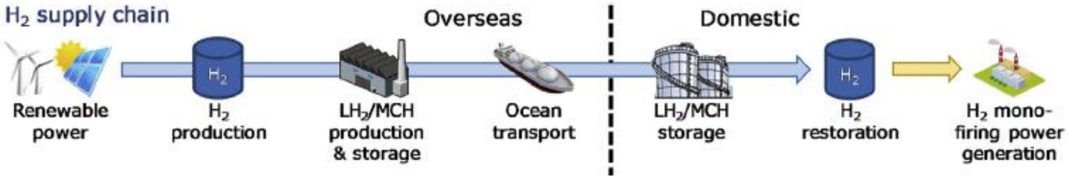


Figure 57. The supply chain of Green Hydrogen with which results are compared with those obtained in this study (Ozawa et al., 2019).

3.5 Sensitivity analysis

Different sensitivity analyses are performed, first only considering the infrastructure of the LH PHS plant (analyses 1 and 2), and afterwards also considering the electricity consumption, using wind power as baseline (analyses 3 and 4). Since the focus of this report lies on GWP, WUPD and ADP-E, only these categories will be assessed, this applies to all the sensitivity analyses below, although results with all the impact categories mentioned in the Commission Recommendation (EU) 2021/2279 of 15 December (THE EUROPEAN COMMISSION, 2021), are depicted in Annex 1.

3.5.1 Analysis 1. Dam lifetime

To see the impact of the dam's lifetime, three scenarios besides the baseline are set up. The baseline considers 100 years of infrastructure, while the other scenarios consider 50, 125 and

200 years. Below, in Table 13 the conditions imposed in the LCA model for the operation of the plant in the different scenarios are shown.

Since the life of the plant is a changing variable, the electricity produced and the maintenance needed will vary. This analysis returns the results shown below in Figure 58 and Tables 14 and 15.

Table 13. Conditions of the Sensitivity Analysis 1, Dam lifetime.

	50 Years	**Baseline – 100 Years**	**125 Years**	**200 Years**
Reference flow	1 kWh	1 kWh	1 kWh	1 kWh
Electricity produced	1.46E+11	2.92E+11	3.65E+11	5.84E+11
Dam construction	1	1	1	1
Electromechanical equipment	1	1	1	1
Maintenance	1	3	4	7

These results show that the longer the life of the dam, the smaller the impacts per kWh will be. This can be intuitive, as the footprint of the dam can be shared over the years it is used. However, as shown in the contribution analysis, the relevance of the dam in the overall project for the different impact categories varies. When looking at GHG emissions, the dam accounts for 16.2%, whereas for water use and abiotic depletion, the civil infrastructure is not that relevant.

When looking at the results, an asymmetry between the reduction of emissions by making the dam life longer and their increase when shortening the dam life is stated.

It is argued that this happens because the dam footprint remains the same, although the time changes, dividing the total footprint of the dam by the number of years. This fact has two implications. The first and most obvious one is that, if the number of years is bigger, the environmental damages of the dam will be lower per kWh, and vice versa. The second fact is that electricity gains relevance in the emissions over time, having a smaller share of 'responsibility' for the emissions in the short-term and a bigger in the long run. This fact would justify the different behaviour in the emissions when making the life of the dam longer or shorter.

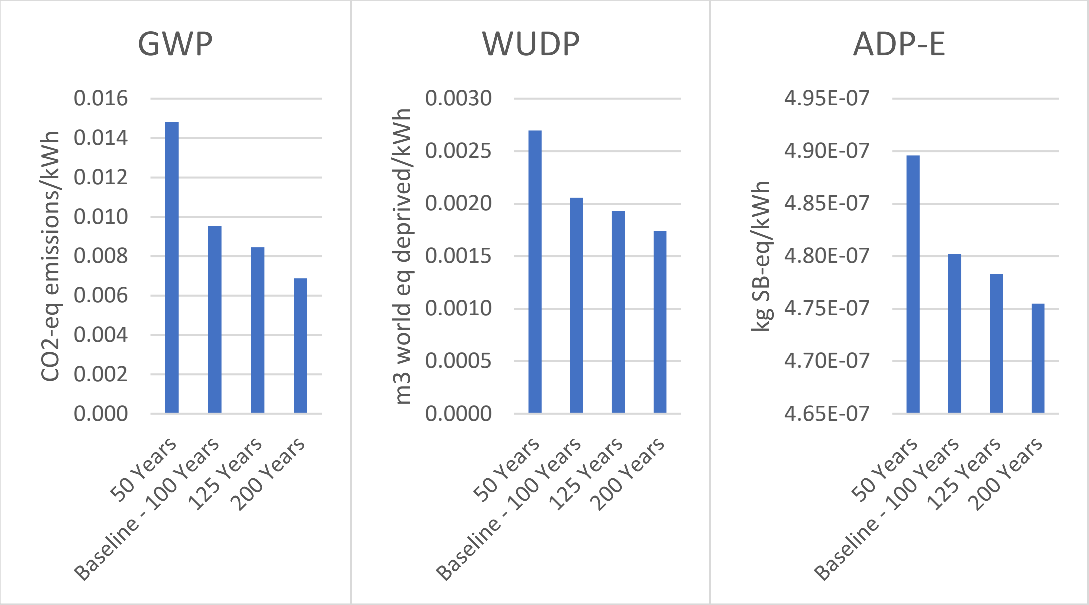


Figure 58. Results for the first sensitivity analysis in the three impact categories.

However, it does not affect the same way to all categories, ADP-E, for example, is barely affected. This is not very well represented in the graph, whereas, in Table 15, the increase or decrease in a percentage rate is shown, painting the cells in red when the emissions are higher and in green when they are lower than the baseline. Here it can be seen that ADP-E performance gets worse by almost a 2% when decreasing the lifetime of the dam to 50 years and improves by almost 1% when the dam is set to 200 years.

Table 14. Results for the first sensitivity analysis in the three impact categories.

	GWP	WUDP	ADP-E
Electricity LH PHS - 50 Years	0.0148	0.0027	4.896E-07
Baseline - 100 Years	0.0095	0.0021	4.802E-07
Electricity LH PHS - 125 Years	0.0085	0.0019	4.783E-07
Electricity LH PHS - 200 Years	0.0069	0.0017	4.755E-07

Table 15. Percentage differences between the scenarios and the baseline.

	Performance improvement		
	GWP	**WUDP**	**ADP-E**
50 Years	55.70%	31.02%	1.96%
125 Years	-11.14%	-6.20%	-0.39%
200 Years	-27.85%	-15.51%	-0.98%

3.5.2 Analysis 2. Electromechanical equipment lifetime

Electromechanical equipment plays one of the major roles in terms of emissions. In this analysis, it is hypothesised that the lifetime of this equipment changes, needing more or less maintenance during the lifetime of the dam, considered to be 100 years. Also, the total output of electricity is assumed to be the same, 2.92e11kWh during the same lifetime. Below, in Table 16 the conditions imposed in the LCA model for the different scenarios are shown.

Table 16. Conditions of the Sensitivity Analysis 2, Electromechanical equipment lifetime.

	Electromechanical Life 20 Years	**Baseline – 25 Years**	**Electromechanical life 33 Years**
Reference flow	1 kWh	1 kWh	1 kWh
Electricity produced	2.92E+11	2.92E+11	2.92E+11
Dam construction	1	1	1
Electromechanical equipment	1	1	1
Maintenance	4	3	2

As depicted in Figure 59 and Tables 17 and 18, the results of this analysis scale linearly. When the lifetime of the electromechanical equipment is increased to 33 years, GHG emissions, water use and elements depletion go down roughly by 10%, 15% and 20% of the total impact of the project. Whereas when the lifetime is 20 years the same results can be seen but in the opposite direction. This is intuitive and not at all surprising, however, these results scale linearly with the number of equipment that is needed, but it is not linear with regards to the timescale. Meaning that is easier to emit more than it is to emit fewer. This is because going from the baseline of 25 years to each alternative there are +8 and -5 years. On the other hand, this highlights the importance of good maintenance and the relevance of this equipment in the environmental impacts within the overall picture.

Table 17. Results for the second sensitivity analysis in the three impact categories

	GWP	**WUDP**	**ADP-E**
20 Years	0.0106	0.0024	5.98E-07
Baseline - 25 Years	0.0095	0.0021	4.80E-07
33 Years	0.0085	0.0017	3.62E-07

Table 18. Percentage differences between the scenarios and the baseline.

	Performance improvement		
	GWP	**WUDP**	**ADP-E**
20Years	9.97%	14.71%	19.69%
33Years	-9.97%	-14.71%	-19.69%

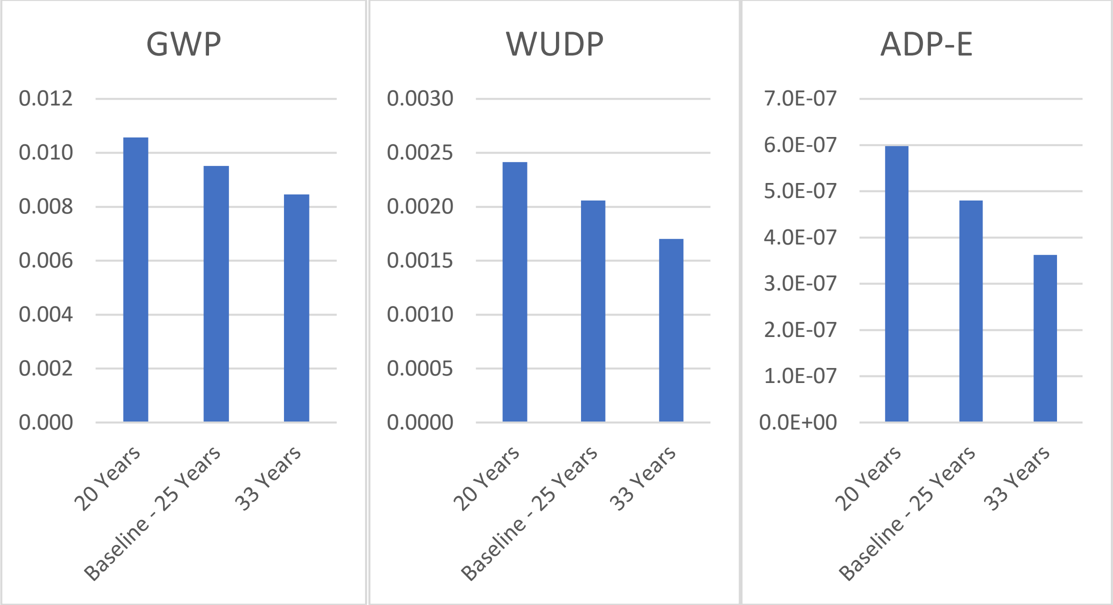


Figure 59. Results for the second sensitivity analysis in the three impact categories

3.5.3 Analysis 3. Reservoir capacity

A commonly used analysis in LCA about PHS plants is playing with the reservoir capacity (Gemechu & Kumar, 2022). In this case, the capacity of the plant has been changed from producing 8GWh/day to 10, 16 and 4GWh/day, which is the same as saying an increase of 25% and 100% and a decrease of 50% of reservoir capacity. This affects directly the electricity produced during the whole life of the plant but also impacts the electricity needs of the same. Below, in Table 19 the conditions imposed in the LCA model for the different scenarios are shown. These conditions assume that the infrastructure needed is the same, which means that the dam, equipment and maintenance needed in 100 years does not change but the amount of water that the reservoir holds does. Results are shown in Figure 60 and Tables 20 and 21.

Table 19. Conditions of the Sensitivity Analysis 3, Reservoir capacity.

	Capacity 4GWh/day	Baseline – 8GWh/day WIND	Capacity 10GWh/day	Capacity 16GWh/day
Reference flow	1 kWh	1 kWh	1 kWh	1 kWh
Electricity produced	1.46E+11	2.92E+11	3.65E+11	5.84E+11
Dam construction	1	1	1	1
Electromechanical equipment	1	1	1	1
Maintenance	3	3	3	3
e- used Wind	1.46E+11	2.92E+11	3.65E+11	5.84E+11
e- losses Wind	6.26E+10	1.25E+11	1.56E+11	2.50E+11

These results show similar trends as the ones presented in the first sensitivity analysis, showing timid improvements when capacity grows and drastic worsening when capacity shrinks. It is argued that this change in performance is due to a similar reason as in the first sensitivity analysis. The impacts of electricity production do not vary when the functional unit is kWh (as it is in this case) because relevant factors like efficiency are not changed, these impacts just scale. However, in this study, there is another part that generates emissions besides electricity production, the infrastructure. It is assumed that civil and electromechanical infrastructure acquire more or less relevance as electricity production varies. This would explain the similar proportion of results as in the first sensitivity analysis. However, differences in ADP-E in this first analysis are indeed non-existing, whereas, in this case, electromechanical equipment is taken into consideration, which is part of the infrastructure that does have an important role in the element needs of the project, justifying this way the increase and decrease of this category.

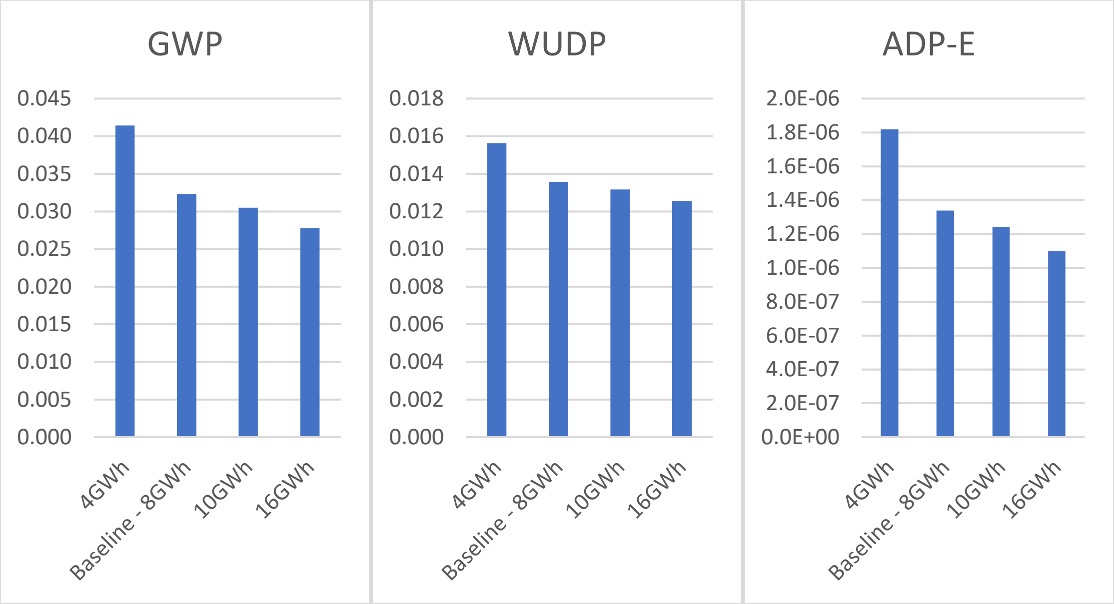


Figure 60. Results for the third sensitivity analysis in the three impact categories.

Table 20. Results for the third sensitivity analysis in the three impact categories.

	GWP	**WUDP**	**ADP-E**
4GWh	0.0414	0.0156	1.818E-06
Baseline - 8GWh	0.0323	0.0136	1.337E-06
10GWh	0.0305	0.0132	1.241E-06
16GWh	0.0278	0.0126	1.098E-06

Table 21. Percentage differences between the scenarios and the baseline.

	Performance improvement		
	GWP	WUDP	ADP-E
4GWh	28.19%	15.10%	35.91%
10GWh	-5.67%	-3.05%	-7.21%
16GWh	-14.08%	-7.53%	-17.94%

3.5.4 Analysis 4. The efficiency of the plant

As mentioned in earlier parts of this report, the electricity intake is divided into used and lost electricity. For this analysis, it is assumed that the electricity generated in the LH PHS plant does not change, which means that the efficiency will directly affect the electricity losses. Moreover, it is important to remember the importance of the role of electricity in terms of emissions, since outweighs by far the emissions from the infrastructure for GWP and WUDP. Thus, in this analysis the focus is on studying the possible ranges in which the technology gets, going from 60% to 80%, glancing at potential future efficiencies of 90% and then looking at the overall impact of the losses itself, with a 100% efficient plant. Below, in Table 22 the conditions imposed in the LCA model for the different scenarios are shown. It is important to remember that this analysis comes with the premise that the LH HPS plant runs with wind electricity, so the impacts of the electricity generation are mainly derived from the production of windmills (fix and moving parts) that will eventually generate electricity. This analysis returns the results shown below in Figure 61 Table 23.

Table 22. Conditions of the Sensitivity Analysis 4, Plant efficiency.

	60% efficiency	Baseline – 70%	80% efficiency	90% efficiency	100% efficiency
Reference flow	1 kWh	1 kWh	1 kWh	1 kWh	1 kWh
Electricity produced	2.92E+11	2.92E+11	2.92E+11	2.92E+11	2.92E+11
Dam construction	1	1	1	1	1
Electromechanical equipment	1	1	1	1	1
Maintenance	3	3	3	3	3
e- used Wind	2.92E+11	2.92E+11	2.92E+11	2.92E+11	2.92E+11
e- losses Wind	1.95E+11	1.25E+11	7.30E+10	3.24E+10	0

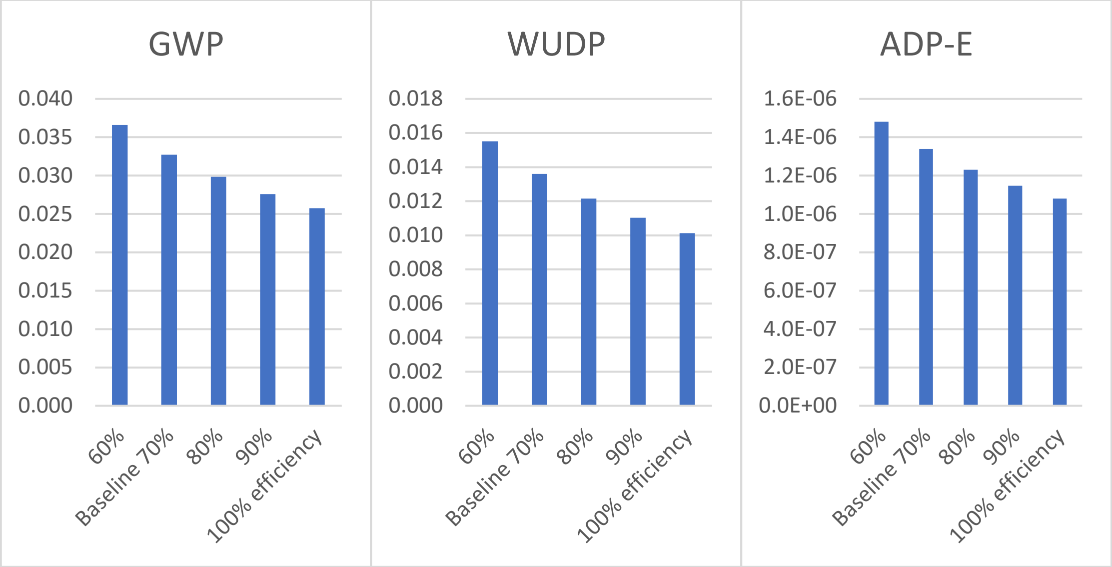


Figure 61. Results for the fourth sensitivity analysis in the three impact categories.

These results show that there is a correlation between GHG emissions and the efficiency of the plant, however, now is possible to quantify the relevance of the losses. If the efficiency is lowered from 70% to 60%, GHG emissions rise by 12%, whereas if the efficiency is increased from 70% to 80% or 90% these emissions are lowered by almost 9% and 16% respectively. Finally, when pushed to 100% efficiency, it shows that there is an improvement of 21.3%, showing the total weight that electricity losses have in a 70% efficiency scenario. Similar results are shown for WUDP and ADP-E, which can be seen in Tables 23 and 24.

The question that rises now is, why these results do not scale with the same proportion as the efficiency? It does (up to a certain point because there are also infrastructure emissions to consider in the overall), however, because the output of electricity is not changed, the total electricity varies accordingly. This can be graphically seen in Figure 62, where the total electricity needs, GWP, WUDP and ADP-E for the different efficiencies are depicted in graphs and where the same segmented line shape can be seen.

Table 23. Results for the fourth sensitivity analysis in the three impact categories.

	GWP	WUDP	ADP-E
60% efficiency	0.0366	0.0155	1.481E-06
Baseline 70%	0.0327	0.0136	1.338E-06
80% efficiency	0.0298	0.0122	1.231E-06
90% efficiency	0.0276	0.0110	1.147E-06
100% efficiency	0.0258	0.0101	1.081E-06

Table 24 Results for the forth sensitivity analysis in the three impact categories.

	Performance improvement		
	GWP	WUDP	ADP-E
60% Efficiency	11.82%	14.14%	10.69%
80% Efficiency	-8.87%	-10.61%	-8.01%
90% Efficiency	-15.76%	-18.86%	-14.25%
100% Efficiency	-21.28%	-25.46%	-19.23%

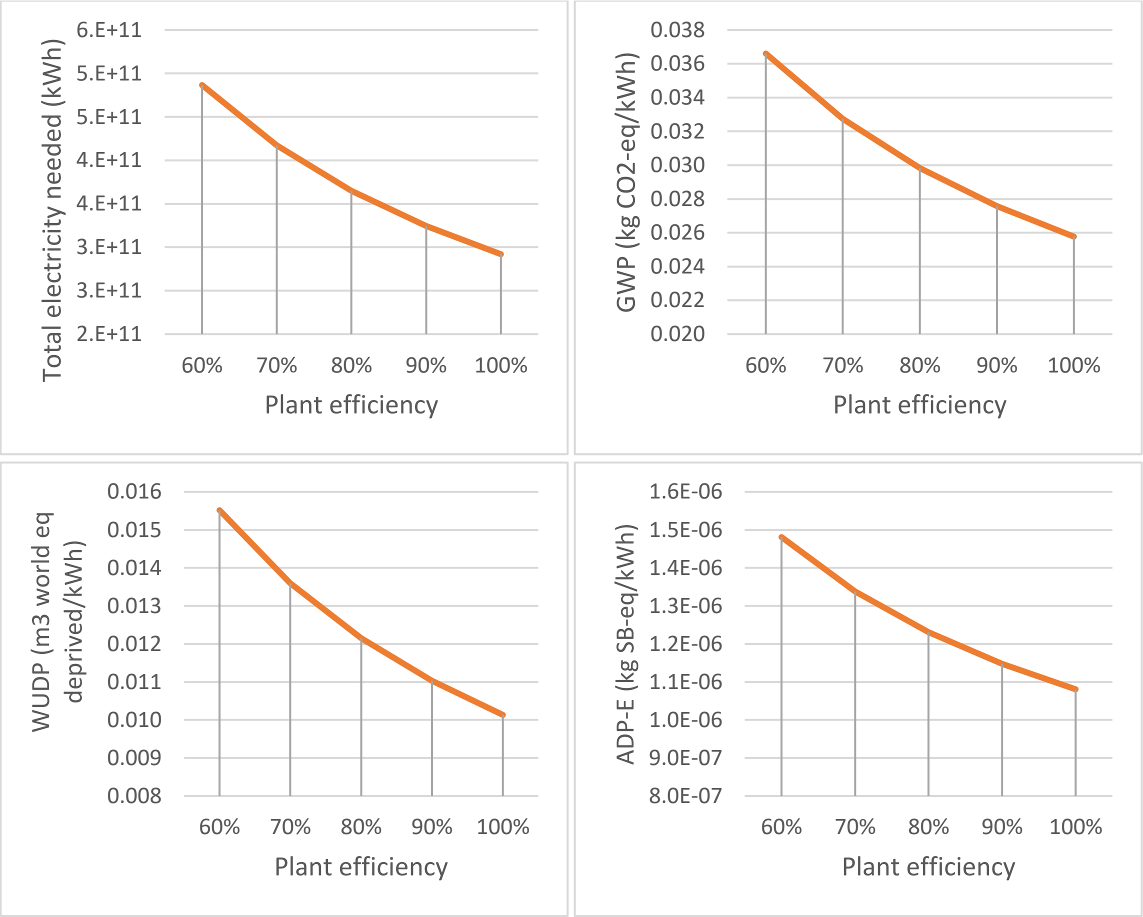


Figure 62. Curves depending on plant efficiency for Total electricity produced, GWP, WUDP and ADP-E.

4 Discussion

4.1 Limitations

This project has many limitations, and a lot of them have already been mentioned in the report. This section aims to be a summary of the most relevant (but not an extensive list) limitations of this study.

4.1.1 Compared technologies set up

Models made for this study are simplifications of reality, especially those for LFP Batteries and Green Hydrogen. This arises problems with the consistency of the alternatives since the LH PHS scenario has been extensively researched and the two other options have not. Which can affect the results obtained, underestimating the alternatives to LH PHS. For that reason, they are compared with results from literature, Figure 63 shows a comparison of the results from this project with those from the literature for the three technology alternatives. Note that, results shown in Figure 63 for LH PHS and LFP Batteries only consider the infrastructure needs, ignoring the electricity ones for both the calculations and the literature results. Whereas for green Hydrogen the infrastructure is ignored in the calculations of this report but they are accounted for in literature.

When looking at the results from other PHS studies (those shown in Table 12) that take into account plants with a similar or bigger installed capacity to the one of this project (2000MW), it is seen that the results from LH PHS are not far from those of conventional PHS, whether it is compared with those results with biogenic emissions or those without.

For LFP Batteries the results shown in literature vary greatly, going from 9.3g of CO2-eq/kWh (Xu et al., 2022) to 77.3 g of CO2-eq/kWh (Peters et al., 2017). Results from this study (only considering the batteries) reach 25.1 g of CO2-eq/kWh which is in the middle between the two values from literature.

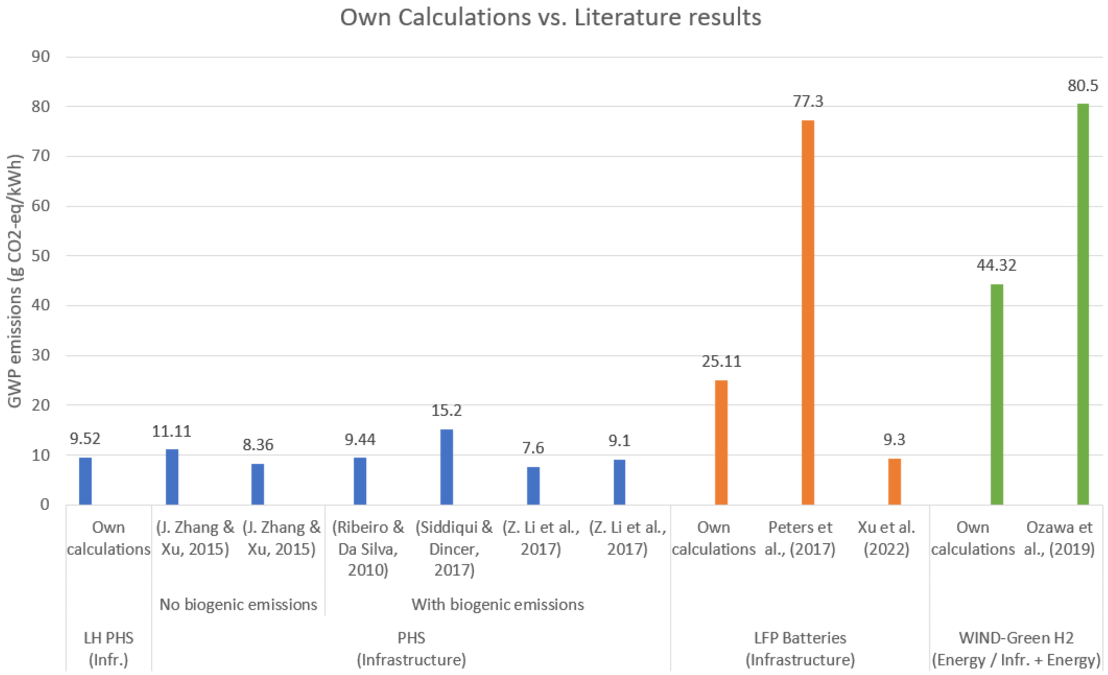


Figure 63. Comparison of values for the different technologies calculated in this study with results from the literature.

On the other hand, for modelling the hydrogen alternative only the electricity needs and the efficiencies for the technologies have been used, ignoring the infrastructure needs. Thus, the impacts linked to this alternative may be far from reality, where infrastructure plays a role. This should be considered when looking at the results, and consider that happens for all the indicators shown in this report.

4.1.2 End-of-life

The LCA of this report has ignored the EOL stage of the plant and the waste flows of the construction, maintenance and operation. This happens for all the alternatives considered in their different scenarios analysed. Thus, the environmental costs estimated are not complete and the recyclability of different equipment is not taken into account. Nonetheless, it is considered that the impacts of the EOL stage are not relevant enough to change the overall results obtained. This might seem contradictory with other PHS studies that consider that the GWP from the decommissioning stage can be 3 times bigger than those of the construction (Gemechu & Kumar, 2022; Mallia & Lewis, 2013). This is based on a study from Pacca (2007) where the decommissioning of hydroelectric dams is studied. More specifically, it studies the emissions derived from the sedimented organic carbon in the soil which, after drying the area releases GHG. However, as explained in previous sections, no biogenic emissions have been considered in this study in either the operation or the decommissioning stage of the LH PHS plant because there is no flooding or drying phase in this project, different to traditional hydroelectric projects. For this reason and because there is no information from other studies on the emissions from physically decommissioning a hydroelectric power plant, the emissions from this stage are not considered.

Another important limitation in this stage is that circularity and recyclability are not considered in this report, something that in reality is expected to happen. For example, the impacts of electromechanical equipment and off-shore wind electricity production are expected to be repaired, re-used, re-purposed and/or recycled appropriately, when they reach the end of their lifetime, making their footprint lower than what is estimated in this report. The same argument could be used when considering Li-ion Batteries, which, in the scenario used for this study, they are thrown away after their determined lifetime. However, it is expected that these batteries are given a second life after their use in storing and delivering electricity to the grid, lowering the environmental costs of the infrastructure needed for their deployment.

4.1.3 Other impact categories

Although 16 different impact categories are reported in this study, they have not been assessed due to time restraints, and many more are left out of these estimations. Even water use could be further assessed since no evaporation has been taken into account because of the dimensions of the dam (5km diameter) and its location (North Sea); however, this fact might be relevant if this project is considered in a warmer geography. Thus, diving deeper into the different impact categories can provide enough information on to tackle different hotspots and make optimal decisions.

Furthermore, special attention should be paid to one indicator that is one of the most important impact categories for the environment, biodiversity. The complexity that entails working with this category made it unfeasible to consider in this report. Nonetheless, several remarks can be done regarding maritime biodiversity.

Dredging activities have many physical and biological effects on biodiversity in the seabed, but also in the water column where these activities take place. Just to number a few from Gubbay (2003) (non-exhaustive list):

- Change in the suspended sediment concentrations and turbidity of the water column in the dredged area but also in the areas where a plume of fine material is suspended.
- The degree to which turbidity affects the area depends on the character of the material being removed and the hydrodynamic conditions of the site. It will not affect the same way in places where there is high turbidity in a natural way like in areas of soft sediment and shallow water that are constantly disturbed by wave and tidal action, such as the Southern part of the North Sea.
- The removal of aggregates can have short- and long-term effects on the seabed due to the change in sediment composition.
- Dredging activities remove benthos from the seabed, affecting these species in a very obvious and direct way. However, these species are part of an ecosystem that is affected indirectly (mobile species like fish or plankton) due to the removal of benthos (affecting food chains), the deposition of material on spawning grounds and the turbidity of the water generated.
- Water chemistry is also affected, with decreasing levels of oxygen due to disturbed layers of anaerobic sediment, mobilization of heavy metals, and release of organic materials in the sediments, among other reasons.

Moreover, the construction of a dam in the North Sea will cause a physical separation of fauna and flora, impeding fishes, plankton and other species to go in, out or through the space where the plant is planned, which could affect migration routes from different animals, among other problems.

On the other hand, it is a great unknown what will eventually happen regarding biodiversity and further research is needed. An example of that is the fact that off-shore windmills have increased biodiversity in the Northern Sea (C. Li et al., 2023). It could be possible that after the destruction caused by the construction of the site, with some time and (maybe) some human intervention, the site could also help strengthen marine biodiversity.

4.2 Results Discussion

The infrastructure required for the plant assessed is expected to last 100 years, which means that future technological developments will make some parts of this model outdated, e.g. Electromechanical replacements under the Maintenance phase and the ship technology that would transport these materials. Therefore, it is assumed that there is an overestimation of the material needs in that section of the project, with higher emissions than what will most likely happen. At the same time, this fact could compensate for neglecting other sections of an LH PHS plant like the ones already mentioned like cooling systems and piping.

4.2.1 GWP, WUDP and ADP-E

In this report, the environmental impacts on the infrastructure of a LH PHS plant are estimated to be the following:

- GWP, 2.8Mt of CO2-eq,
- WUDP, 601 million m3 of water, 2.5 million,
- ADP-E140.2t of SB-eq,
- Material requirements:
  - 2.5 million tonnes of concrete
  - 120 million tonnes of sand
  - 24.6 million tonnes of granite
  - 357 thousand tonnes of steel (different alloys)
  - 11 thousand tonnes of copper
  - 555 tonnes of magnets

These numbers seem very high when looking at them from an absolute point of view, however, results in this report make clear the fact clear that infrastructure construction plays a minor role when compared with electricity production, especially when this electricity is sourced from fossil fuels. When looking at GHG emissions, the production of electricity from wind sources and the grid is 2.4 and 77 times bigger than the CO2-eq emissions from the infrastructure. For water use, the electricity from windpower and from the grid are 5.6 and almost 38 times bigger than the infrastructure needs. The majority of these emissions come from the material needs for the production of windmills in the first scenario and from the use of gas and coal in the second. Water use also explodes when electricity supply is considered, multiplying by almost 6 and 38 the consumption of water from the wind and the Dutch grid. The root of the emissions here in the wind scenario is also in the material needs for the windmills. However, in the case of the grid scenario changes a bit from the GWP case, adding nuclear and solar-photovoltaic electricity generation to the production methods that were also present for the major GHG emissions. The use of elements in the scenarios where electricity is considered almost two-fold the material requirements for the LH PHS plant, leaving its infrastructure to play a more relevant role than in the previous indicators. Albeit the absolute number in this impact category does not change much in these two scenarios, their composition does. In the wind scenario, copper, chromite and lead have a prominent role; whereas in the Dutch grid mix scenario, these previously mentioned metals play an important role but also silver has an important share of the contributions. These differences come from the electricity source, in the grid, the scenario should be emphasised that solar energy (which contributes to 9% of the electricity mix) accounts for more than 40% of the environmental footprint in this category.

From these results, there are some relevant facts to highlight. First of all, when looking at only the LH PHS infrastructure, the most relevant sources of emissions differ between category indicators. For GWP, the civil infrastructure outweighs by little the electromechanical equipment (55.7% and 44.1%), whereas for WUDP and ADP-E, the electromechanical equipment footprint alone reaches almost 70% and 98% respectively. Considering this, if emissions want to be reduced, the right category indicator should be selected and the proposed solution should be assessed for all the different category indicators to be sure that one problem is not substituted by another. Second, when electricity input is taken into consideration, different electricity production methods perform differently in the several impact categories. Besides coal and gas for GWP, seems relevant to highlight the case of nuclear for WUDP and solar-photovoltaic for WUDP and ADP-E. This is because nuclear energy provides 3.2% of the Dutch grid mix and is responsible for 7.4% of the water use, whereas solar-photovoltaic reaches 9.4% of the grid mix and causes 19.6% of the water use and 41.2% of the material depletion. This shows that, inevitably, the energy transition will increase the environmental pressure in some points, while releasing the pressure from others.

When comparing technologies the results show a similar picture as in the electricity scenario, where the environmental footprint skyrockets when using electricity from the grid. In this scenario, however, uncertainties are modelled due to the consideration of different efficiency scenarios and, in the case of LFP Batteries, also considering different lifetimes for the batteries. This concludes in a range of values for each category indicator and having different technologies that perform the best depending on the scenario considered. For GWP and WUDP the picture is roughly the same, in the wind scenario, LH

PHS is the best-performing technology followed by LFP Batteries and Green Hydrogen. However, when the uncertainties are considered, then batteries become the best or the worst performing, whereas LH PHS and Green Hydrogen remain quite stable around their average values. In the Dutch grid scenario, LH PHS is outperformed by Batteries due to their higher efficiency rates in almost all the scenarios for these two categories. Differently from the LH PHS case, LFP Batteries infrastructure plays a very relevant role when looking at emissions for GWP and WUDP in the wind scenarios. Their weight is more than half for these categories. In the grid scenario, Batteries do not play an important role in GWP and account for barely 15% of WUDP. On the other hand, for ADP-E, no matter which electricity or efficiency scenario is looked at, LFP Batteries are always outperformed. When looking at the Batteries' weight in this category, it is seen that their infrastructure needs account for more than 80% in both scenarios.

It should be noted some facts that derive from these insights. First, the uncertainty due to the efficiency changes varies widely between technologies. LFP batteries present higher uncertainty than the other two options, which remain closer to the average value. This concludes the fact that LFP Batteries can be the best and the worst-performing technologies in some cases depending on the scenario that is being looked at. Nonetheless, it is also true that the results presented in this report differ from other results from the literature. As noted in a previous section, emissions from the infrastructure of LFP batteries could triple and overall emissions of Green Hydrogen could be multiplied by 2 or by 5, depending on the electricity sources. On the other hand, it should be emphasised the fact that the environmental weight of the infrastructure differs from LH PHS and LFP Batteries. In the former, the weight of the construction and the equipment is always smaller than the burdens from the electricity production, whereas, in the latter, the infrastructure claims a more relevant role. This is due to the difference in efficiencies and due to the use of different materials and devices in the development of the technologies. Moreover, this highlights their hotspots, meaning that LH PHS, is more relevant to lower the emissions in the production of electricity production infrastructure than in the infrastructure of its plant. On the contrary, if improvements want to be made in the LFP Batteries, the focus should be put on the development of cleaner ways of producing these devices.

4.2.2 Materials use

The LH PHS plant uses enormous amounts of materials, they are depicted in Table 25 with its share of 'responsibility' for the three different category indicators for the total infrastructure. This shows there is a great use of materials in this project, and although they might not be considered in the ADP-E results, some of them are scarce, like sand (Torres et al., 2021). Sand is not only used by dredgers to create the inner berm, but also it is used for the production of concrete, and the sand needed for this purpose cannot be sourced from deserts but is usually mined from terrestrial deposits or hard rock deposits (Torres et al., 2021). Beyond this, as an act of transparency, it should be noted the fact that granite emissions are derived from literature and not from the ecoinvent database. Considering its important role in the emissions of this report, it might be revised and checked in further studies.

Table 25. Material needs with its share of emissions for the LH PHS infrastructure.

				Percentage of the infrastructure emissions		
				GWP	**WUDP**	**ADP-E**
Reinforced concrete	Concrete	2,532,288	tonnes	17%	5.77%	-
	Steel	158,268	tonnes	11.8%	24.3%	-
Inner berm	Sand	122,702,091	tonnes	-	-	-
Foundations + Protecting layer	Granite	24,682,331	tonnes	22%	-	-
Turbines	Electrical steel	11,326	tonnes	0.8%	-	-
	Copper	11,326	tonnes	-	2.29%	25%
	Stainless Steel	157,072	tonnes	28%	34.3%	14.1%
	Steel	31,554	tonnes	2.04%	2.63%	-
	Magnet	555	tonnes	-	-	-
Subsea cable		60	km	2.29%	6.99%	23.9%
Electronics	Steel (46%) Electric steel (46%) Copper (2.8%)	1059	tonnes	4.87%	8.48%	33.6%
			Total	88.80%	84.76%	96.60%

These material quantities contrast with those from LFP Li-ion Batteries in that, although they are high, they don't reach the scale of LH PHS. On the other hand, LFP batteries use Critical Raw Materials like Lithium. Due to the size of the storage assessed, the number of materials required to carry it out is enormous, so much so that the share of infrastructure in the total footprint (considering electricity inputs) for GWP, WUDP and ADP-E is bigger for LFP Batteries than for LH PHS. Just to see the proportions of a LFP storage facility of the capacity of the LH PHS plant presented in this project, the current biggest electricity farm for Li-ion batteries is the "Victorian Big Battery" (Lystianingrum et al., 2023), which has a capacity of 300MW. This is eight times less than the project proposed in this study. Furthermore, there is a social aspect that is usually not considered when talking about material use that is a direct consequence of the mining of these metals. However, the relevance of these social issues is gaining everyday more importance, and thus, this damage to the people mining metals should not be forgotten when taking into consideration the alternatives on the table.

For the three storing technologies, as well as for the electricity production sources, circularity considerations should be taken into account. This model fails to account for the improvements derived from proper EoL management of these technologies. Right now, only major metals like steel, copper or aluminium are recovered through (mainly) recycling, whereas devices with metals in smaller quantities, like Li-ion Batteries, are usually not recovered due to their economic unfeasibility (Wang et al., 2022).

4.2.3 Energy density

Energy density is the term used to estimate the amount of area or volume used to store a certain amount of energy. In this case, volume is used to compare the LH PHS details with other technologies. It is already known that the energy density will be low since traditional PHS plants have already a low value for energy density and the concept of LH PHS is based on using more area with lower high differences. However, it is still important to quantify this factor and compare it with other technologies to provide a full picture with all the relevant characteristics to be able to compare different alternatives in a fair mode.

Before showing the results, it is important to explain how these estimations have been done (at least for the LH PHS case). For this calculation what is needed is the amount of electricity production in a full discharge and the volume of the infrastructure needed. In this case, the electricity output considered is 8GWh per discharge and an area of a cylinder with 5022m of diameter and 25m high. While having a 5000m diameter, this diameter considers half of the Caissons, with means that 22 meters have to be added. This operation results in 4.95e8m3, which at the same time derives in an outcome of 0.02kWh/m3. On the other side, for the calculations of LFP batteries, data for energy density is taken from Zoller et al. (2020), which is given in Wh/kg and, using the volumetric density from Seo et al. (2018) it could be translated into kWh/m3. These values are 568Wh/kg and 3600kg/m3, which turns into 2044.8kWh/m3. These results and the comparison with other technologies are shown in Table 26.

Table 26. The energy density of the different compared technologies.

	Energy density	Unit	Source
LH PHS	0.02	kWh/m3	Own calculations
LFP Li-ion Batteries	2045	kWh/m3	Own calculations with data from (Seo et al., 2018; Zoller et al., 2020)
H2 Liquid	2370	kWh/m3	(Edwards et al., 2007)
H2 (200bar)	530	kWh/m3	(Edwards et al., 2007)

As expected, the energy density for LH PHS is very low. With a value of 0.02kWh/m3 is far from the Li-ion batteries or the hydrogen results, which range from 530-2370 kWh/m3. These results however have to be considered with the total electricity storing capacities of the different technologies. Because efficiency and energy density are important factors, the total output has also to be considered. Since the energy transition comes with the challenge of producing and storing enormous amounts of electricity, the more efficient the better. However, there is no point in being very efficient in terms of land if the total electricity needed cannot be supplied.

Moreover, Hameer & Van Niekerk (2015) made a summary where the power capacity of multiple technologies is shown, in their study, Li-ion batteries have a capacity of 0.1MW, whereas traditional PHS range from 100-5000MW. Things have indeed changed and there are large-scale Li-ion battery farms storing electricity with a range of 2MW to 300MW (Lystianingrum et al., 2023). Nevertheless, it should be mentioned that there is still a big difference between a capacity of 300MW from the Li-ion batteries farms and the 5000MW of the PHS ones. On the other hand, this technology still has to mature, whilst PHS is pretty much already developed (although in this study LH HPS is aimed).

4.2.4 Land use

Following the discussion of Energy density, but going more in-depth about what it means in terms of land use, LH PHS area is estimated to be 19.63 km2, to have an idea of what these dimensions mean, Delft city measures 24.1 km2. These calculations consider the dam of 5km in diameter, if the project is bigger, it would mean the area would also increase, being in any case, a pharaonic construction.

For batteries, the area calculations are not that straightforward because the energy density is estimated in volume and not in the area. This, however, means that the final area will depend on the way batteries are stacked, a lower area will be used if the batteries are vertically pilled; whilst more area will be occupied if they are all disposed at the same height. Nevertheless, knowing that the energy density is more than 100,000 times higher, this area will be far smaller than in the LH PHS project.

Hydrogen on the other hand is even more complicated, as it requires different types of infrastructure for its production, transport and generate electricity from its combustion. But again, having such a higher energy density than LH PHS technology, this area is expected to be much lower.

Finally, some considerations should be taken into account when comparing land use. Especially because this LH PHS project is not planned to be built on land, where other activities like agriculture, industry or urban spaces would compete with and; differently than Batteries and Hydrogen production, which would require inland facilities. Furthermore, traditional PHS projects, which are located inland, sometimes displace people and towns flooded for the sake of the project (Trussart et al., 2002). This fact would be avoided with the adoption of an offshore approach, eliminating this social impact from the equation. Also, to consider is the fact that this project is planned to be in the North Sea, where multiple projects are already, have been, or are being developed. These range from oil and gas extraction platforms, offshore windfarms, subsea cables, Carbon Capture and Storage projects, fishing activities, military activities, etc. (H. D. Smith, 2000; TU Delft, 2021). This is mentioned because it is true that LH PHS does not compete for space as much as if it was developed inland, but still, it should not be thought as the North Sea has all the space to spare for whichever purposes, on the contrary, it is heavily industrialised and it will become even more over time.

4.3 Recommendations

4.3.1 Further Environmental research

The work presented here in this report can serve as a base for future analysis. Some remarks on what should be done in the future are:

Study in more detail the specifics of the plant when the project is more advanced and more information is available. If possible, everything that configures the infrastructure of the plant should be accounted for. Moreover, there are specific engineering requirements that are in place for the proper use of the plant that is not considered in this study. One example would be the duplicity of key equipment and services to ensure the continuous operation of the plant no matter what happens.

It is assumed in this report that no biogenic emissions are produced, either in the operation or in the decommissioning phase. This fact should be studied, quantified and confirmed, since it represents a hotspot for traditional PHS. Furthermore, decommissioning deserves a proper study on its own, knowing not only if there are emissions from biogenic sources, but also shedding some light on the dismantling of the plant and quantifying its impacts seem relevant since there are not many studies regarding this topic. Also, regarding the EoL stage, the circularity of materials should be assessed for both the infrastructure needed for electricity production and its storage. Integrating this knowledge into the model to see the impacts and possibilities of the different materials would allow us to dive a bit deeper into the real picture. Because, for example, steel integrates a big share of emissions, both in CO2-

eq emissions and in water use, but this material is largely recovered through recycling, and thus its footprint should be lower.

Batteries (LFP or whichever type is assessed), together with Green Hydrogen should be modelled with more detail or at least a crosscheck should be done to give more realistic numbers. Right now, the proxies used give an estimation that underestimates the impact they have. This concludes by showing results that make LH PHS not as promising as it truly is.

Looking at a different aspect, having GHG emissions reduction in mind and having it as the main goal is fine for now due to Global Warming problems. However, this problem must not be replaced by another with equal or bigger consequences such as Biodiversity loss could be. Therefore, other category indicators and a complete Environmental Impact Assessment should be performed to assess to help in the design stage and not considered just as a legal requirement. For example, biodiversity and the impacts of marine wildlife- like dredging overall damages, migration routes etc.- should be assessed before construction of this magnitude starts and redesign the project to make it a better place than before, not only to reduce its impacts.

In general, lines, if the concept is proven right and provides the desired results, it should be assessed if this technology can be utilized in other regions of the world where electrification is still starting to develop. It should not be forgotten that Global Warming is a global problem that cannot be solved locally or regionally. Europe becoming net zero by 2050 is always good news, but the developing world should not be forgotten and left alone because if they are, they will choose the cheapest option, which might be fossil fuels solutions and then, the problem of Global Warming remains. Moreover, if this solution is technically feasible, economically viable and environmentally desired, the supply of the materials should be assessed. The scarcity of materials is not only located in critical raw materials but also less fancier materials like sand. Again, local solutions will not solve this problem and there is the risk of using all the materials needed for a green transition only in the regions that come first while other regions still in development are left to their fate.

4.3.2 Further opportunities for the plant

Looking at a different aspect, having GHG emissions reduction in mind and having it as the main goal is fine for now due to Global Warming problems. However, this problem must not be replaced by another with equal or bigger consequences such as Biodiversity loss could be. Therefore, other category indicators and a complete Environmental Impact Assessment should be performed to assess to help in the design stage and not considered just as a legal requirement. Some examples of this are:

- Generation of electricity from different sources using the infrastructure of the dam with:
    - Solar panels, either floating panels or all around the ring of the dam.
    - The implementation of wave harvesting technologies on the outside of the ring.
- Creating aquaculture projects where fish and other synergic species like mussels can be harvested.
- Create a friendly environment in the walls of the dam for different marine species like molluscs, algae, benthos, etc.
- Due to the magnitude of the wind parks planned around the LH PHS plant in the Alpheus project, it could provide a safe space to host wind park employees when they are working on the windmills.
- Research centre hub for, not limited to:
    - Marine life research
    - Testing marine energy generation
    - Oceanographic studies
    - Environmental monitoring
    - Marine Conservation Area
- It could even be studied the feasibility of instead of decommissioning the whole dam, after the lifetime of the plant it could become part of the environment with biodiversity goals.

In essence, it is highly recommended to the developers of this project talk to other actors that can provide complementary projects with synergies and improve the impact of the LH PHS plant.

5 Conclusions

In this thesis, the environmental performance of LH PHS technology has been assessed using the LCA methodology with the ultimate goal is to answer the proposed research questions:

What is the environmental footprint of the construction, operation and maintenance of a Low Head Pumped Hydro Storage plant and how does it compare to that of other energy storage technologies?

- *What are the environmental impacts linked to the construction of the offshore LH PHS?*
- *What are the environmental impacts linked to the storage of electricity in LH PHS?*
- *How does storing electricity with LH PHS compare with other technologies such as LFP batteries and Green Hydrogen?*

To answer this question, different setups have been used (scopes, scenarios…). This has resulted in analysing the LH PHS infrastructure on its own, with electricity coming from wind sources and from the 2021 Dutch grid mix and comparing these results with LFP Li-ion batteries and with Green Hydrogen from the wind. Moreover, GWP, WUDP and ADP-E have been thoroughly assessed.

LH PHS infrastructure total emissions go up to 2.8Mt of CO2-eq, 601 million m3 of water and 140.2 tonnes of Sb-eq. The origin of these emissions differs by category indicator, for GWP the emissions between civil and electromechanical infrastructure are shared in a 56/44 ratio; whereas the WUDP ratio is 31/69, and ADP-E is 98/2. This shows that reducing emissions is not enough to target one part of the infrastructure but all of it has to be assessed.

When electricity comes into the equation, the footprint of the LH PHS infrastructure becomes a rather small portion of the overall. Looking only at the scenario where electricity is provided by offshore windmills, their emissions per kWh for GWP, WUDP and ADP-E are respectively 2.4, 5.6 and 1.8 times bigger than the emissions from the infrastructure. These emissions come mainly from the production of material for the fixed and moving parts of offshore wind turbines.

When LH PHS is compared with LFB Batteries and Green Hydrogen (considering wind electricity input), the results from the different assessed impact categories are not so dissimilar. Green Hydrogen is always outperformed by LH HPS technology in the assessed categories, while LFP Batteries tend to perform better than LH PHS for GWP and WUDP by a little, but not in the ADP-E category, where they are the worst performer.

From these facts, some major conclusions can be drawn.

- First, for LH PHS, the performance of the electricity supply is more important than the one of the infrastructures and therefore, the most effective way of reducing its environmental impacts is to store clean energy and avoid the use of grid electricity, as long as fossil fuels are still a major contributor to it; and increasing its efficiency. Whereas for LFP Batteries, the infrastructure plays a bigger role than the electricity input. Thus, to reduce emissions here, the technology itself should be targeted.
- Second, LH PHS presents itself as a technology with similar environmental performance as LFP Batteries in terms of GWP and WUDP. However, the materials used in these two alternatives are very different and is something to consider when choosing one alternative over the other. Moreover, these two options could be seen as complementary because when the use of renewables becomes majoritarian, the amount of electricity needed to be stored will be too big for one technology to handle, besides the importance of diversification in the energy sector.

Going back to the energy transition, factors like efficiency and energy density are very important, however, it should be always kept in mind that a big output is required, and scale in this case matters. The biggest real project involving Li-ion batteries ever built is eight times smaller in terms of storage capacity than the project considered in this study (Lystianingrum et al., 2023). On the other hand, known technologies like PHS could do the job, although these come with doubts regarding its real GHG footprint due to biogenic emissions, the need for mountains for its development and social challenges due to displacement of people and towns, among others. Moreover, material consideration should be at the core of the decision-making process, not only the amount of material needed for the project but also the circularity of the materials and components that configure the different technologies. Further research should be done regarding the EoL stage of LH PHS to assess the circularity of the materials and the plant itself and its decommission.

Finally, as with all big projects, a complete Environmental Impact Assessment will be needed for its development and implementation. However, it is strongly advised to the developers of the LH PHS project and their engineers, to use this report to re-design the plant and not to consider this document just as a legal requirement. Using their inputs to not only reduce the footprint of the plant but to improve the environmental performance of the area with their project.

6 References

ABB. (2003). *Power Transformer TrafoStar 500 MVA.* https://search.abb.com/Library/Download.aspx?DocumentID=SEEPD_TPT_TrafoStar0001_1&DocumentPartId=&

Alessia, A., Alessandro, B., Maria, V.-G., Carlos, V.-A., & Francesca, B. (2021). Challenges for sustainable lithium supply: A critical review. *Journal of Cleaner Production, 300*, 126954. https://doi.org/10.1016/j.jclepro.2021.126954

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M. A., Kinnaird, J., Littleboy, A., Meinert, L. D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., & Yakovleva, N. (2017). Mineral supply for sustainable development requires resource governance. *Nature, 543*(7645), 367–372. https://doi.org/10.1038/nature21359

Alsaleh, A., & Sattler, M. (2019). Comprehensive life cycle assessment of large wind turbines in the US. *Clean Technologies and Environmental Policy*, *21*(4), 887–903. https://doi.org/10.1007/s10098-019-01678-0

Altiparmak, S. O. (2022). China and Lithium Geopolitics in a Changing Global Market. *Chinese Political Science Review*. https://doi.org/10.1007/s41111-022-00227-3

Arvesen, A., Birkeland, C., & Hertwich, E. G. (2013). The Importance of Ships and Spare Parts in LCAs of Offshore Wind Power. *Environmental Science & Technology*, *47*(6), 2948–2956. https://doi.org/10.1021/es304509r

Asdrubali, F., Baldinelli, G., D'Alessandro, F., & Scrucca, F. (2015). Life cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews, 42*, 1113–1122. https://doi.org/10.1016/j.rser.2014.10.082

Braga, A. M., Silvestre, J. D., & de Brito, J. (2017). Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *Journal of Cleaner Production, 162*, 529–543. https://doi.org/10.1016/j.jclepro.2017.06.057

Briones Hidrovo, A., Uche, J., & Martínez-Gracia, A. (2017). Accounting for GHG net reservoir emissions of hydropower in Ecuador. *Renewable Energy, 112*, 209–221. https://doi.org/10.1016/j.renene.2017.05.047

Calvo, G., & Valero, A. (2022). Strategic mineral resources: Availability and future estimations for the renewable energy sector. *Environmental Development*, *41*, 100640. https://doi.org/10.1016/j.envdev.2021.100640

CBS. (2021). *How much water do we consume? - The Netherlands in numbers 2021 | CBS* [Webpagina]. How much water do we consume? - The Netherlands in numbers 2021 | CBS. https://longreads.cbs.nl/the-netherlands-in-numbers-2021/how-much-water-do-we-consume

CEU. COMMU. (2019). *What is the European Green Deal?.* Publications Office. https://data.europa.eu/doi/10.2775/275924

Chen, X., Shen, W., Vo, T. T., Cao, Z., & Kapoor, A. (2012). An overview of lithium-ion batteries for electric vehicles. *2012 10th International Power & Energy Conference (IPEC)*, 230–235. https://doi.org/10.1109/ASSCC.2012.6523269

Cooper, D., & Gustafsson, T. (2004). *Methodology for calculating emissions from ships: 1. Update of emission factors.* https://urn.kb.se/resolve?urn=urn:nbn:se:naturvardsverket:diva-7084

Cuyper, J.-B. D. (2014). *SMART, SUSTAINABLE: A LIFE CYCLE APPROACH TO FUEL ECONOMY AS APPLIED TO DREDGING VESSELS.* https://trid.trb.org/view/1344986

DELFT UNIVERSITY OF TECHNOLOGY. (n.d.). *Overview of Potential Sites and Construction Methodology* (Alpheus Project). DELFT UNIVERSITY OF TECHNOLOGY.

DEMEGroup (Director). (2023, February 28). *Construction of the world's first energy island.* https://www.youtube.com/watch?v=SBs8MX7qAjI

Dufo-López, R., Cortés-Arcos, T., Artal-Sevil, J. S., & Bernal-Agustín, J. L. (2021). Comparison of Lead-Acid and Li-Ion Batteries Lifetime Prediction Models in Stand-Alone Photovoltaic Systems. *Applied Sciences*, *11*(3), Article 3. https://doi.org/10.3390/app11031099

Edwards, P. P., Kuznetsov, V. L., & David, W. I. F. (2007). Hydrogen energy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1853), 1043–1056. https://doi.org/10.1098/rsta.2006.1965

EMEA Head Offices—TenCate Geosynthetics. (n.d.). Geosynthetics. Retrieved 21 May 2023, from https://www.tencategeo.eu/en/contact-us/our-emea-head-offices

Equipment | Van Oord/. (2023). https://www.vanoord.com/en/equipment/

The European Green Deal, (2019). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

European Commission. (2019, December 11). *The European Green Deal* [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691

Fan, E., Li, L., Wang, Z., Lin, J., Huang, Y., Yao, Y., Chen, R., & Wu, F. (2020). Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. *Chemical Reviews, 120*(14), 7020–7063. https://doi.org/10.1021/acs.chemrev.9b00535

Fleet and equipment | Boskalis. (2023). Royal Boskalis Westminster NV. https://boskalis.com/about-us/fleet-and-equipment

Gagnon, L., Bélange, C., & Uchiyama, Y. (2002). Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy, 30 (14),* 1267–1278.

Gallo, A. B., Simões-Moreira, J. R., Costa, H. K. M., Santos, M. M., & Moutinho dos Santos, E. (2016). Energy storage in the energy transition context: A technology review. *Renewable and Sustainable Energy Reviews, 65,* 800–822. https://doi.org/10.1016/j.rser.2016.07.028

Gao, T., Fan, N., Dai, T., **北京西城百万庄大街**26**号**, **百万庄大街**26**号**, & **北京市朝阳区来广**营高科技产业园创达二路1**号**. (2022). Lithium extraction from hard rock lithium ores: Technology, resources, environment and cost. *China Geology, 0*(0), 0–0. https://doi.org/10.31035/cg2022088

Gasper, P., Collath, N., Hesse, H. C., Jossen, A., & Smith, K. (2022). Machine-Learning Assisted Identification of Accurate Battery Lifetime Models with Uncertainty. *Journal of The Electrochemical Society, 169*(8), 080518. https://doi.org/10.1149/1945-7111/ac86a8

Gemechu, E., & Kumar, A. (2022). A review of how life cycle assessment has been used to assess the environmental impacts of hydropower energy. *Renewable and Sustainable Energy Reviews, 167,* 112684. https://doi.org/10.1016/j.rser.2022.112684

Gubbay, A. (2003). *Marine aggregate extraction and biodiversity.* https://www.fc.up.pt/pessoas/ptsantos/azc-docs/gubbay-marine_agregate_extr_and_biodiversity.pdf

Guinée, J. B. (Ed.). (2002). *Handbook on life cycle assessment: Operational guide to the ISO standards*. Kluwer Academic Publishers.

Hainsch, K., Löffler, K., Burandt, T., Auer, H., Crespo del Granado, P., Pisciella, P., & Zwickl-Bernhard, S. (2022). Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal? *Energy*, *239*, 122067. https://doi.org/10.1016/j.energy.2021.122067

Hameer, S., & Van Niekerk, J. L. (2015). A review of large-scale electrical energy storage: This paper gives a broad overview of the plethora of energy storage. *International Journal of Energy Research*, *39*(9), 1179–1195. https://doi.org/10.1002/er.3294

Hiremath, M., Derendorf, K., & Vogt, T. (2015). Comparative Life Cycle Assessment of Battery Storage Systems for Stationary Applications. *Environmental Science & Technology*, *49*(8), 4825–4833. https://doi.org/10.1021/es504572q

Hoffstaedt, J. P., Truijen, D. P. K., Fahlbeck, J., Gans, L. H. A., Qudaih, M., Laguna, A. J., De Kooning, J. D. M., Stockman, K., Nilsson, H., Storli, P.-T., Engel, B., Marence, M., & Bricker, J. D. (2022). Low-head pumped hydro storage: A review of applicable technologies for design, grid integration, control and modelling. *Renewable and Sustainable Energy Reviews*, *158*, 112119. https://doi.org/10.1016/j.rser.2022.112119

Hosen, M. S., Jaguemont, J., Van Mierlo, J., & Berecibar, M. (2021). Battery lifetime prediction and performance assessment of different modeling approaches. *IScience*, *24*(2), 102060. https://doi.org/10.1016/j.isci.2021.102060

IEA. (2022). *IEA – International Energy Agency*. IEA. https://www.iea.org/countries/the-netherlands

ISO. (2006). *ISO 14044—Environmental management—Life cycle assessment—Requirements and guidelines.*

Javed, M. S., Ma, T., Jurasz, J., & Amin, M. Y. (2020). Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. *Renewable Energy*, *148*, 176–192. https://doi.org/10.1016/j.renene.2019.11.157

Jorge, R. S., Hawkins, T. R., & Hertwich, E. G. (2012). Life cycle assessment of electricity transmission and distribution—part 2: Transformers and substation equipment. *The International Journal of Life Cycle Assessment*, *17*(2), 184–191. https://doi.org/10.1007/s11367-011-0336-0

Kalair, A., Abas, N., Saleem, M. S., Kalair, A. R., & Khan, N. (2021). Role of energy storage systems in energy transition from fossil fuels to renewables. *Energy Storage*, *3*(1). https://doi.org/10.1002/est2.135

Keil, P., Schuster, S., Lüders, C., Hesse, H., Arunachala, R., & Jossen, A. (2015). *Lifetime Analyses of Lithium-Ion EV Batteries.*

Kerr, R. A. (2011). Peak Oil Production May Already Be Here. *Science*, *331*(6024), 1510–1511. https://doi.org/10.1126/science.331.6024.1510

Kharitonov, V., Kabashev, K., & Kurelchuk, U. (2014). *Estimation of uranium mining peak*. https://www.osti.gov/etdeweb/biblio/22594903

Killer, M., Farrokhseresht, M., & Paterakis, N. G. (2020). Implementation of large-scale Li-ion battery energy storage systems within the EMEA region. *Applied Energy*, *260*, 114166. https://doi.org/10.1016/j.apenergy.2019.114166

Lehtola, T. A., & Zahedi, A. (2021). Electric Vehicle Battery Cell Cycle Aging in Vehicle to Grid Operations: A Review. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *9*(1), 423–437. https://doi.org/10.1109/JESTPE.2019.2959276

Li, C., Coolen, J. W. P., Scherer, L., Mogollón, J. M., Braeckman, U., Vanaverbeke, J., Tukker, A., & Steubing, B. (2023). Offshore Wind Energy and Marine Biodiversity in the North Sea: Life Cycle Impact Assessment for Benthic Communities. *Environmental Science & Technology*, *57*(16), 6455–6464. https://doi.org/10.1021/acs.est.2c07797

Li, Z., Du, H., Xiao, Y., & Guo, J. (2017). Carbon footprints of two large hydro-projects in China: Life-cycle assessment according to ISO/TS 14067. *Renewable Energy*, *114*, 534–546. https://doi.org/10.1016/j.renene.2017.07.073

Lu, J., Zhao, S., Sun, Y., & Tang, H. (2018). Gas production peaks in China: Research and strategic proposals. *Natural Gas Industry B*, *5*(4), 371–379. https://doi.org/10.1016/j.ngib.2018.01.011

Lystianingrum, V., Priyadi, A., & Negara, I. M. Y. (2023). Lessons learned from large-scale lithium-ion battery energy storage systems incidents: A mini review. *Process Safety Progress*, *42*(2), 348–355. https://doi.org/10.1002/prs.12448

Maggio, G., & Cacciola, G. (2012). When will oil, natural gas, and coal peak? *Fuel*, *98*, 111–123. https://doi.org/10.1016/j.fuel.2012.03.021

Mahmud, M. A. P., Huda, N., Farjana, S. H., & Lang, C. (2018). Environmental sustainability assessment of hydropower plant in Europe using life cycle assessment. *IOP*

Conference Series: Materials Science and Engineering, *351*, 012006. https://doi.org/10.1088/1757-899X/351/1/012006

Mallia, E., & Lewis, G. (2013). Life cycle greenhouse gas emissions of electricity generation in the province of Ontario, Canada. *The International Journal of Life Cycle Assessment*, *18*(2), 377–391. https://doi.org/10.1007/s11367-012-0501-0

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*(2), e1500323. https://doi.org/10.1126/sciadv.1500323

Molina Gómez, A., Morozovska, K., Laneryd, T., & Hilber, P. (2022). Optimal sizing of the wind farm and wind farm transformer using MILP and dynamic transformer rating. *International Journal of Electrical Power & Energy Systems*, *136*, 107645. https://doi.org/10.1016/j.ijepes.2021.107645

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: A review. *Environmental Chemistry Letters*, *20*(1), 153–188. https://doi.org/10.1007/s10311-021-01322-8

Ozawa, A., Kudoh, Y., Kitagawa, N., & Muramatsu, R. (2019). Life cycle CO2 emissions from power generation using hydrogen energy carriers. *International Journal of Hydrogen Energy*, *44*(21), 11219–11232. https://doi.org/10.1016/j.ijhydene.2019.02.230

Pacca, S. (2007). Impacts from decommissioning of hydroelectric dams: A life cycle perspective. *Climatic Change*, *84*(3–4), 281–294. https://doi.org/10.1007/s10584-007-9261-4

Padey, P., Blanc, I., Le Boulch, D., & Xiusheng, Z. (2012). A Simplified Life Cycle Approach for Assessing Greenhouse Gas Emissions of Wind Electricity. *Journal of Industrial Ecology*, *16*, S28–S38. https://doi.org/10.1111/j.1530-9290.2012.00466.x

Pang, M., Zhang, L., Wang, C., & Liu, G. (2015). Environmental life cycle assessment of a small hydropower plant in China. *The International Journal of Life Cycle Assessment*, *20*(6), 796–806. https://doi.org/10.1007/s11367-015-0878-7

Parra, D., Valverde, L., Pino, F. J., & Patel, M. K. (2019). A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renewable and Sustainable Energy Reviews*, *101*, 279–294. https://doi.org/10.1016/j.rser.2018.11.010

Petavratzi, E., Sanchez-Lopez, D., Hughes, A., Stacey, J., Ford, J., & Butcher, A. (2022). The impacts of environmental, social and governance (ESG) issues in achieving sustainable lithium supply in the Lithium Triangle. *Mineral Economics*, *35*(3), 673–699. https://doi.org/10.1007/s13563-022-00332-4

Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews*, *67*, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

Popp, H., Attia, J., Delcorso, F., & Trifonova, A. (2014, April 15). *Lifetime analysis of four different lithium ion batteries for (plug – in) electric vehicle.*

Rastler, D. (2010). *Electricity Energy Storage Technology Options. A White Paper Primer on Applications, Costs, and Benefits.*

Rehman, S., Al-Hadhrami, L. M., & Alam, Md. M. (2015). Pumped hydro energy storage system: A technological review. *Renewable and Sustainable Energy Reviews*, *44*, 586–598. https://doi.org/10.1016/j.rser.2014.12.040

Ribeiro, F. D. M., & Da Silva, G. A. (2010). Life-cycle inventory for hydroelectric generation: A Brazilian case study. *Journal of Cleaner Production*, *18*(1), 44–54. https://doi.org/10.1016/j.jclepro.2009.09.006

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management*, *80*(1–3), 5–22. https://doi.org/10.1016/j.agwat.2005.07.001

Ritchie, H., Roser, M., & Rosado, P. (2020). CO_2 and Greenhouse Gas Emissions. *Our World in Data*. https://ourworldindata.org/co2/country/netherlands

Ritchie, H., Roser, M., & Rosado, P. (2022). Energy. *Our World in Data*. https://ourworldindata.org/energy/country/netherlands

RSA. (2021). *Ansit and Norit*. Rekefjord Stone. https://en.rekefjord-stone.no/ansit-and-norit/

Schmidt, A. (2006). *Life cycle assessment of electricity delivered from an onshore power plant based on Vestas V82-1.65 MW turbines*. https://windfarmrealities.org/wp-content/uploads/wfr-docs/vestas-v82-lca.pdf

Schreiber, A., Marx, J., & Zapp, P. (2019). Comparative life cycle assessment of electricity generation by different wind turbine types. *Journal of Cleaner Production*, *233*, 561–572. https://doi.org/10.1016/j.jclepro.2019.06.058

Seo, J.-H., Verlinde, K., Guo, J., Heidary, D. S. B., Rajagopalan, R., Mallouk, T. E., & Randall, C. A. (2018). Cold sintering approach to fabrication of high rate performance binderless LiFePO4 cathode with high volumetric capacity. *Scripta Materialia*, *146*, 267–271. https://doi.org/10.1016/j.scriptamat.2017.12.005

Siddiqui, O., & Dincer, I. (2017). Comparative assessment of the environmental impacts of nuclear, wind and hydro-electric power plants in Ontario: A life cycle assessment. *Journal of Cleaner Production*, *164*, 848–860. https://doi.org/10.1016/j.jclepro.2017.06.237

Smith, H. D. (2000). The industrialisation of the world ocean. *Ocean & Coastal Management*, *43*(1), 11–28. https://doi.org/10.1016/S0964-5691(00)00028-4

Smith, P. E. (2016). Design and specification of marine concrete structures. In *Marine Concrete Structures* (pp. 65–114). Elsevier. https://doi.org/10.1016/B978-0-08-100081-6.00003-9

Suwanit, W., & Gheewala, S. H. (2011). Life cycle assessment of mini-hydropower plants in Thailand. *The International Journal of Life Cycle Assessment*, *16*(9), 849–858. https://doi.org/10.1007/s11367-011-0311-9

Swierczynski, M., Stroe, D.-I., Stan, A.-I., Teodorescu, R., & Kær, S. K. (2015). Lifetime Estimation of the Nanophosphate \hboxLiFePO_4\hbox/C Battery Chemistry Used in Fully Electric Vehicles. *IEEE Transactions on Industry Applications*, *51*(4), 3453–3461. https://doi.org/10.1109/TIA.2015.2405500

Tencate. (2019). *Polyfelt*. https://www.tencategeo.eu/media/fa088124-1268-4ffb-9625-f7931ecc82bb/kWFIqA/TenCate%20Geosynthetics/Documents%20EMEA/English%20Europe/Datasheet/Nonwoven%20-%20TenCate%20Polyfelt/TenCate_PolyfeltF_TechicalData_EN_502042.pdf

THE EUROPEAN COMMISSION,. (2021). Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. In *OJ L* (Vol. 471). http://data.europa.eu/eli/reco/2021/2279/oj/eng

Toro, N., Robles, P., & Jeldres, R. I. (2020). Seabed mineral resources, an alternative for the future of renewable energy: A critical review. *Ore Geology Reviews*, *126*, 103699. https://doi.org/10.1016/j.oregeorev.2020.103699

Torres, A., Brandt, J., Lear, K., & Liu, J. (2017). A looming tragedy of the sand commons. *Science*, *357*(6355), 970–971. https://doi.org/10.1126/science.aao0503

Torres, A., Simoni, M. U., Keiding, J. K., Müller, D. B., Zu Ermgassen, S. O. S. E., Liu, J., Jaeger, J. A. G., Winter, M., & Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene. *One Earth*, *4*(5), 639–650. https://doi.org/10.1016/j.oneear.2021.04.011

Trussart, S., Messier, D., Roquet, V., & Aki, S. (2002). Hydropower projects: A review of most effective mitigation measures. *Energy Policy*, *30*(14), 1251–1259. https://doi.org/10.1016/S0301-4215(02)00087-3

TU Delft. (2021). *Overview of Potential Sites and Construction Methodology. LOW HEAD SEA WATER PUMP STORAGE DEVELOPMENT NORTH SEA*.

United Nations. (2015). *Adoption of the Paris Agreement, 21st Conference of the Parties.* https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Van Oers, L., Guinée, J. B., & Heijungs, R. (2020). Abiotic resource depletion potentials (ADPs) for elements revisited—Updating ultimate reserve estimates and introducing time series for production data. *The International Journal of Life Cycle Assessment*, *25*(2), 294–308. https://doi.org/10.1007/s11367-019-01683-x

Verán-Leigh, D., & Vázquez-Rowe, I. (2019). Life cycle assessment of run-of-river hydropower plants in the Peruvian Andes: A policy support perspective. *The International Journal of Life Cycle Assessment*, *24*(8), 1376–1395. https://doi.org/10.1007/s11367-018-01579-2

Wang, M., Liu, K., Dutta, S., Alessi, D. S., Rinklebe, J., Ok, Y. S., & Tsang, D. C. W. (2022). Recycling of lithium iron phosphate batteries: Status, technologies, challenges, and prospects. *Renewable and Sustainable Energy Reviews*, *163*, 112515. https://doi.org/10.1016/j.rser.2022.112515

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Xu, C., Steubing, B., Hu, M., Harpprecht, C., van der Meide, M., & Tukker, A. (2022). Future greenhouse gas emissions of automotive lithium-ion battery cell production. *Resources, Conservation and Recycling*, *187*, 106606. https://doi.org/10.1016/j.resconrec.2022.106606

Zhang, J., & Xu, L. (2015). Embodied carbon budget accounting system for calculating carbon footprint of large hydropower project. *Journal of Cleaner Production, 96,* 444–451. https://doi.org/10.1016/j.jclepro.2013.10.060

Zhang, S., Pang, B., & Zhang, Z. (2015). Carbon footprint analysis of two different types of hydropower schemes: Comparing earth-rockfill dams and concrete gravity dams using hybrid life cycle assessment. *Journal of Cleaner Production, 103,* 854–862. https://doi.org/10.1016/j.jclepro.2014.06.053

Zoller, F., Böhm, D., Luxa, J., Döblinger, M., Sofer, Z., Semenenko, D., Bein, T., & Fattakhova-Rohlfing, D. (2020). Freestanding LiFe0.2Mn0.8PO4/rGO nanocomposites as high energy density fast charging cathodes for lithium-ion batteries. *Materials Today Energy, 16,* 100416. https://doi.org/10.1016/j.mtener.2020.100416

7 Annexes

7.1 Annex 1. Results for all indicators

This annex presents the tables with the results for all the category indicators from the Commission Recommendation (EU) 2021/2279 of 15 December 2021 (THE EUROPEAN COMMISSION, 2021)transparency purposes.

The following sections are divided according to the results they represent.

7.1.1 Electricity Comparison Scenarios

Table S1. Results for all category indicators estimated in this study for the LH PHS plant in the three electricity scenarios.

Category Indicator	Scenario	LH PHS
GWP Global warming potential (kg CO2 Eq)	No energy	0.0095
	Wind	0.0327
	NL mix 2021	0.7439
ODP Ozone depletion potential (kg CFC-11-Eq)	No energy	1.3E-10
	Wind	4.55E-10
	NL mix 2021	2.96E-08
HTC Human toxicity: carcinogenic (CTUh)	No energy	7.48E-11
	Wind	2.32E-10
	NL mix 2021	2.07E-10
HTNC Human toxicity: non-carcinogenic (CTUh)	No energy	2.54E-10
	Wind	1.32E-09
	NL mix 2021	3.18E-09
PMF Particulate matter formation (disease incidence)	No energy	5.66E-10
	Wind	2.42E-09
	NL mix 2021	8.45E-09
IR Ionising radiation (kBq U235-Eq)	No energy	0.0006
	Wind	0.0016
	NL mix 2021	0.0367
POF Photochemical oxidant formation (kg NMVOC-Eq)	No energy	3.8E-05
	Wind	0.00014
	NL mix 2021	0.00197
AE Acidification (mol H+-Eq)	No energy	6.99E-05
	Wind	0.00022
	NL mix 2021	0.00182
ET Eutrophication: terrestrial (mol N-Eq)	No energy	0.00012
	Wind	0.00039
	NL mix 2021	0.00709
EF	No energy	5.06E-06

Eutrophication: freshwater (kg P-Eq)	Wind	1.49E-05
	NL mix 2021	0.00012
EM Eutrophication: marine (kg N-Eq)	No energy	1.23E-05
	Wind	4.16E-05
	NL mix 2021	0.00063
EXF Ecotoxicity: freshwater (CTUe)	No energy	0.062
	Wind	0.223
	NL mix 2021	0.917
LU(Q) Land use, soil quality index (dimensionless)	No energy	0.037
	Wind	0.130
	NL mix 2021	2.50
WUDP Water use, user deprivation potential (m3 world eq deprived)	No energy	0.002
	Wind	0.014
	NL mix 2021	0.080
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	No energy	4.8E-07
	Wind	1.34E-06
	NL mix 2021	1.34E-06
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	No energy	0.082
	Wind	0.350
	NL mix 2021	11.22

7.1.2 Technology Comparison Scenarios

Table S2. Results for all category indicators estimated in this study for the three technology alternatives for the electricity and efficiency scenarios.

Category Indicator	Scenarios	LH PHS	LFP Batteries	Green Hydrogen
GWP Global warming potential (kg CO2 Eq)	Wind - LOW	0.03661	0.0327	0.05194
	Wind - MID	0.03274	0.0273	0.04432
	Wind - TOP	0.02984	0.0245	0.03864
	NL mix - LOW	0.86633	0.6550	-
	NL mix - MID	0.74394	0.5660	-
	NL mix - HIGH	0.65214	0.5273	-
ODP Ozone depletion potential (kg CFC-11-Eq)	Wind - LOW	5.09E-10	6.73E-10	7.27E-10
	Wind - MID	4.55E-10	5.50E-10	6.21E-10
	Wind - TOP	4.14E-10	4.83E-10	5.41E-10
	NL mix - LOW	3.45E-08	2.61E-08	-
	NL mix - MID	2.96E-08	2.26E-08	-
	NL mix - HIGH	2.59E-08	2.11E-08	-
HTC Human toxicity: carcinogenic (CTUh)	Wind - LOW	2.59E-10	1.69E-10	3.53E-10
	Wind - MID	2.32E-10	1.43E-10	3.01E-10
	Wind - TOP	2.13E-10	1.31E-10	2.62E-10
	NL mix - LOW	2.29E-10	1.47E-10	-
	NL mix - MID	2.07E-10	1.25E-10	-
	NL mix - HIGH	1.91E-10	1.14E-10	-
HTNC Human toxicity: non-carcinogenic (CTUh)	Wind - LOW	1.50E-09	2.71E-09	2.39E-09
	Wind - MID	1.32E-09	2.20E-09	2.04E-09
	Wind - TOP	1.19E-09	1.92E-09	1.77E-09
	NL mix - LOW	3.66E-09	4.34E-09	-
	NL mix - MID	3.18E-09	3.61E-09	-
	NL mix - HIGH	2.81E-09	3.23E-09	
PMF Particulate matter formation (disease incidence)	Wind - LOW	2.73E-09	3.81E-09	4.14E-09
	Wind - MID	2.42E-09	3.12E-09	3.53E-09
	Wind - TOP	2.19E-09	2.74E-09	3.08E-09
	NL mix - LOW	9.76E-09	9.09E-09	-
	NL mix - MID	8.45E-09	7.69E-09	-
	NL mix - HIGH	7.46E-09	7.00E-09	-
IR Ionising radiation (kBq U235-Eq)	Wind - LOW	0.0018	0.0015	0.0022
	Wind - MID	0.0016	0.0012	0.0019
	Wind - TOP	0.0015	0.0011	0.0016
	NL mix - LOW	0.0427	0.0322	-
	NL mix - MID	0.0367	0.0278	-
	NL mix - HIGH	0.0322	0.0259	-
POF	Wind - LOW	0.00016	0.00015	0.00023
	Wind - MID	0.00014	0.00013	0.00019

Photochemical oxidant formation (kg NMVOC-Eq)	Wind - TOP	0.00013	0.00011	0.00017
	NL mix - LOW	0.00229	0.00175	-
	NL mix - MID	0.00197	0.00151	-
	NL mix - HIGH	0.00173	0.00141	-
AE Acidification (mol H+-Eq)	Wind - LOW	0.00024	0.00047	0.00033
	Wind - MID	0.00022	0.00038	0.00028
	Wind - TOP	0.00020	0.00033	0.00025
	NL mix - LOW	0.00211	0.00187	-
	NL mix - MID	0.00182	0.00159	-
	NL mix - HIGH	0.00160	0.00146	-
ET Eutrophication: terrestrial (mol N-Eq)	Wind - LOW	0.00043	0.00107	0.00061
	Wind - MID	0.00039	0.00085	0.00052
	Wind - TOP	0.00035	0.00073	0.00045
	NL mix - LOW	0.00826	0.00693	-
	NL mix - MID	0.00709	0.00593	-
	NL mix - HIGH	0.00622	0.00547	-
EF Eutrophication: freshwater (kg P-Eq)	Wind - LOW	1.66E-05	2.02E-05	2.21E-05
	Wind - MID	1.49E-05	1.65E-05	1.89E-05
	Wind - TOP	1.37E-05	1.45E-05	1.64E-05
	NL mix - LOW	0.00014	1.11E-04	-
	NL mix - MID	0.00012	9.48E-05	-
	NL mix - HIGH	0.00010	8.76E-05	-
EM Eutrophication: marine (kg N-Eq)	Wind - LOW	4.65E-05	5.12E-05	6.56E-05
	Wind - MID	4.16E-05	4.22E-05	5.59E-05
	Wind - TOP	3.80E-05	3.74E-05	4.88E-05
	NL mix - LOW	0.00074	5.68E-04	-
	NL mix - MID	0.00063	4.90E-04	-
	NL mix - HIGH	0.00055	4.55E-04	-
EXF Ecotoxicity: freshwater (CTUe)	Wind - LOW	0.250	0.341	0.362
	Wind - MID	0.223	0.279	0.308
	Wind - TOP	0.203	0.244	0.269
	NL mix - LOW	1.060	0.948	-
	NL mix - MID	0.917	0.804	-
	NL mix - HIGH	0.810	0.735	-
LU(Q) Land use, soil quality index (dimensionless)	Wind - LOW	0.145	0.162	0.207
	Wind - MID	0.130	0.133	0.176
	Wind - TOP	0.118	0.118	0.154
	NL mix - LOW	2.91	2.235	-
	NL mix - MID	2.50	1.929	-
	NL mix - HIGH	2.19	1.794	-
WUDP Water use, user deprivation potential (m3 world eq deprived)	Wind - LOW	0.0155	0.0153	0.0258
	Wind - MID	0.0136	0.0128	0.0220
	Wind - TOP	0.0122	0.0115	0.0192
	NL mix - LOW	0.0930	0.0734	-

	NL mix - MID	0.0800	0.0631	-
	NL mix - HIGH	0.0703	0.0585	-
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	Wind - LOW	1.48E-06	2.40E-06	1.92E-06
	Wind - MID	1.34E-06	1.94E-06	1.64E-06
	Wind - TOP	1.23E-06	1.68E-06	1.43E-06
	NL mix - LOW	1.48E-06	2.41E-06	-
	NL mix - MID	1.34E-06	1.95E-06	-
	NL mix - HIGH	1.23E-06	1.69E-06	-
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	Wind - LOW	0.395	0.39	0.600
	Wind - MID	0.350	0.32	0.512
	Wind - TOP	0.317	0.29	0.446
	NL mix - LOW	13.07	9.90	-
	NL mix - MID	11.22	8.56	-
	NL mix - HIGH	9.83	7.98	-

7.1.3 Contribution analysis

The layout of this section is placed in Landscape or Portrait form to be able to properly see the Sankey diagrams depicted below.

7.1.4 LH PHS Electricity Scenarios

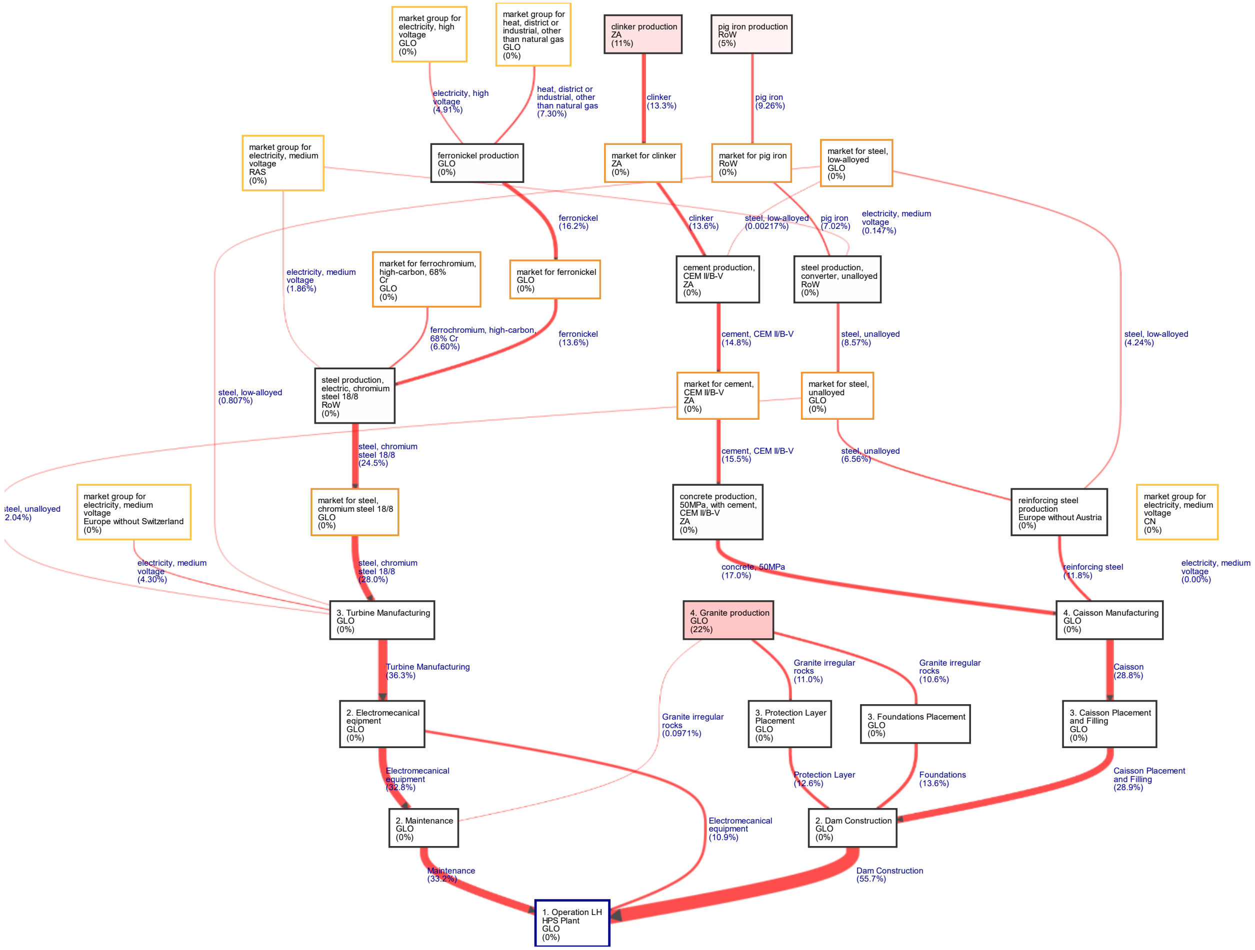


Figure S1. GWP Sankey diagram for the Infrastructure of LH PHS plant.

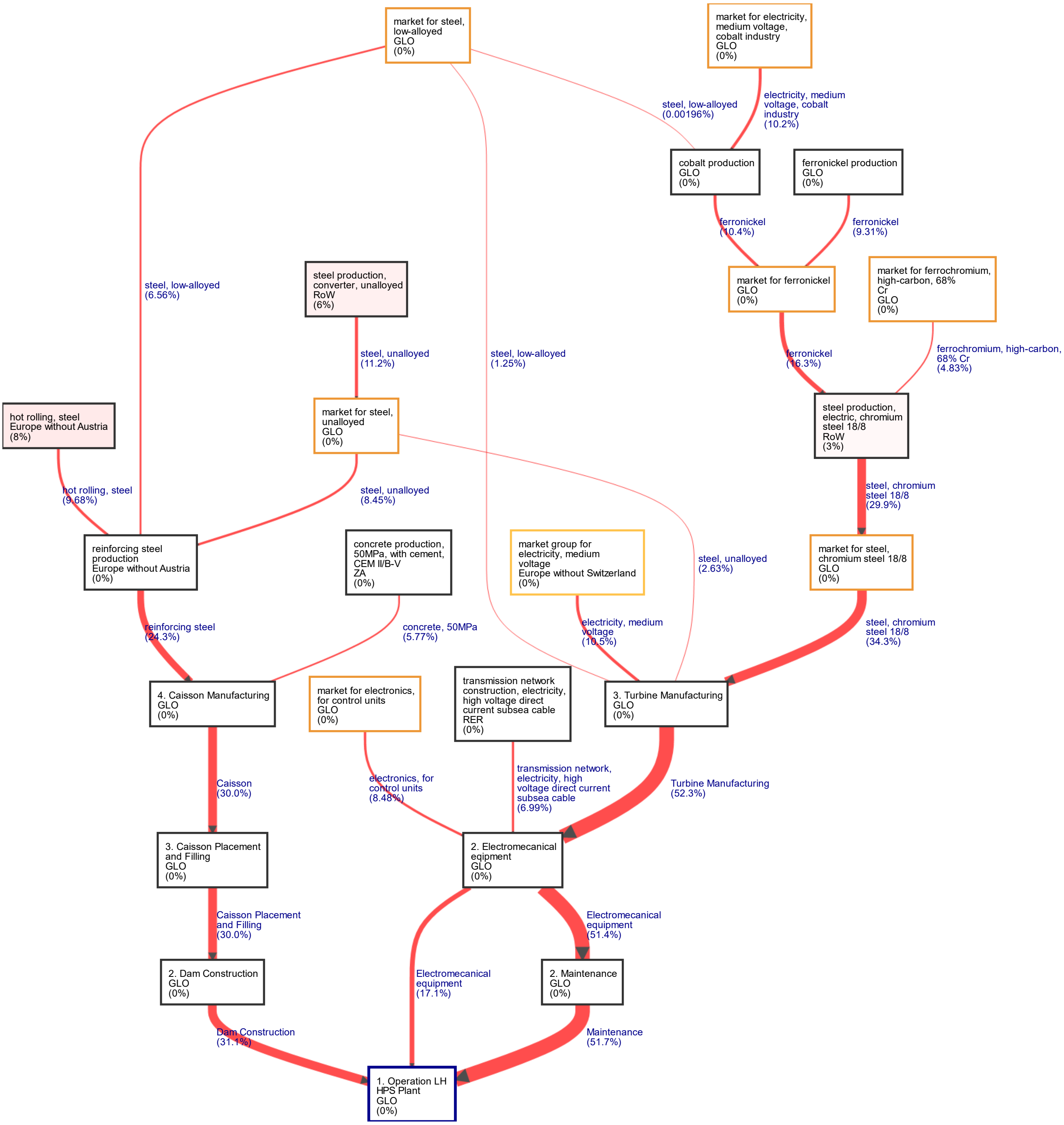


Figure S2. WUDP Sankey diagram for the Infrastructure of LH PHS plant.

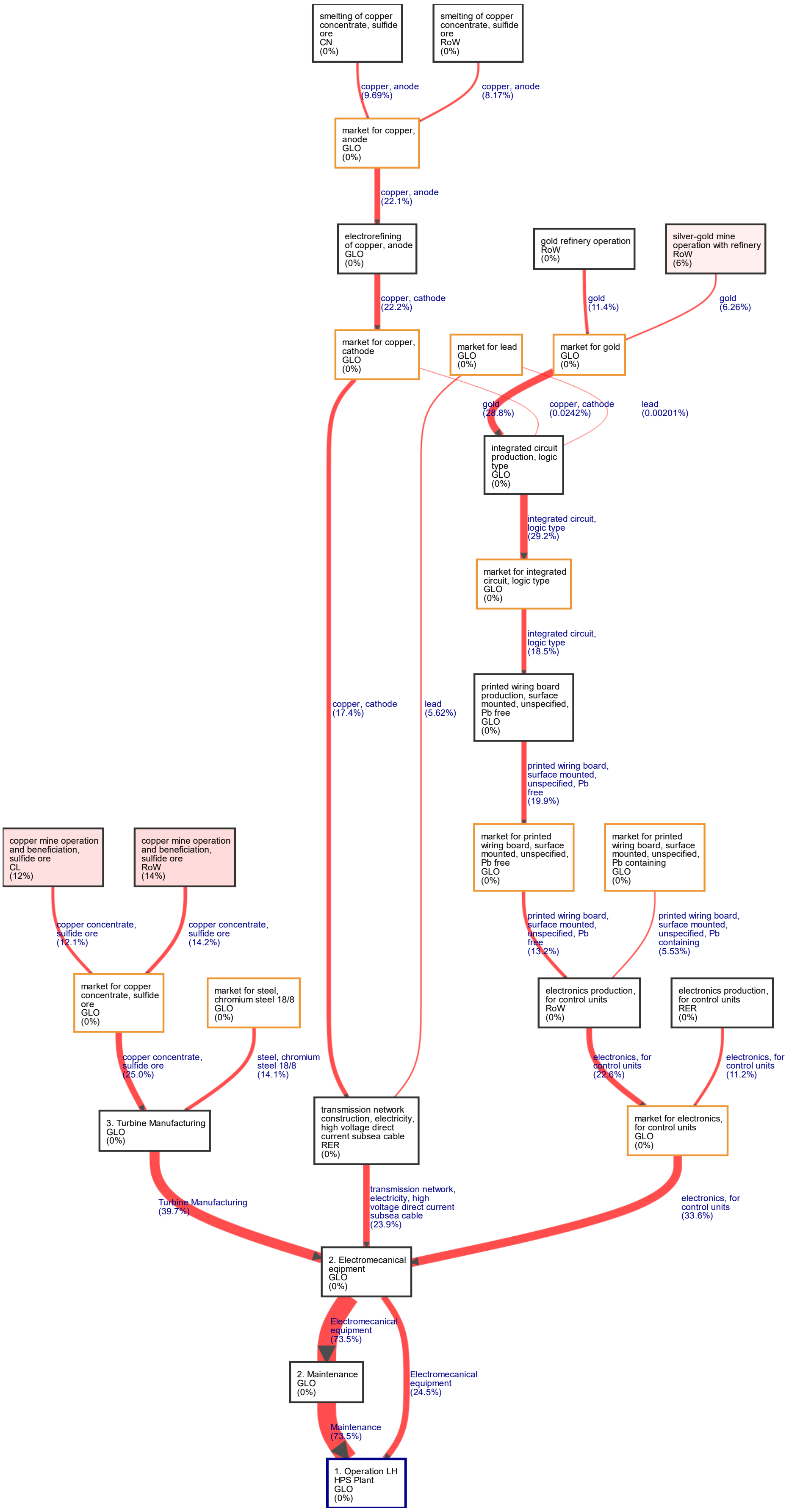


Figure S3. ADP-E Sankey diagram for the Infrastructure of LH PHS plant.

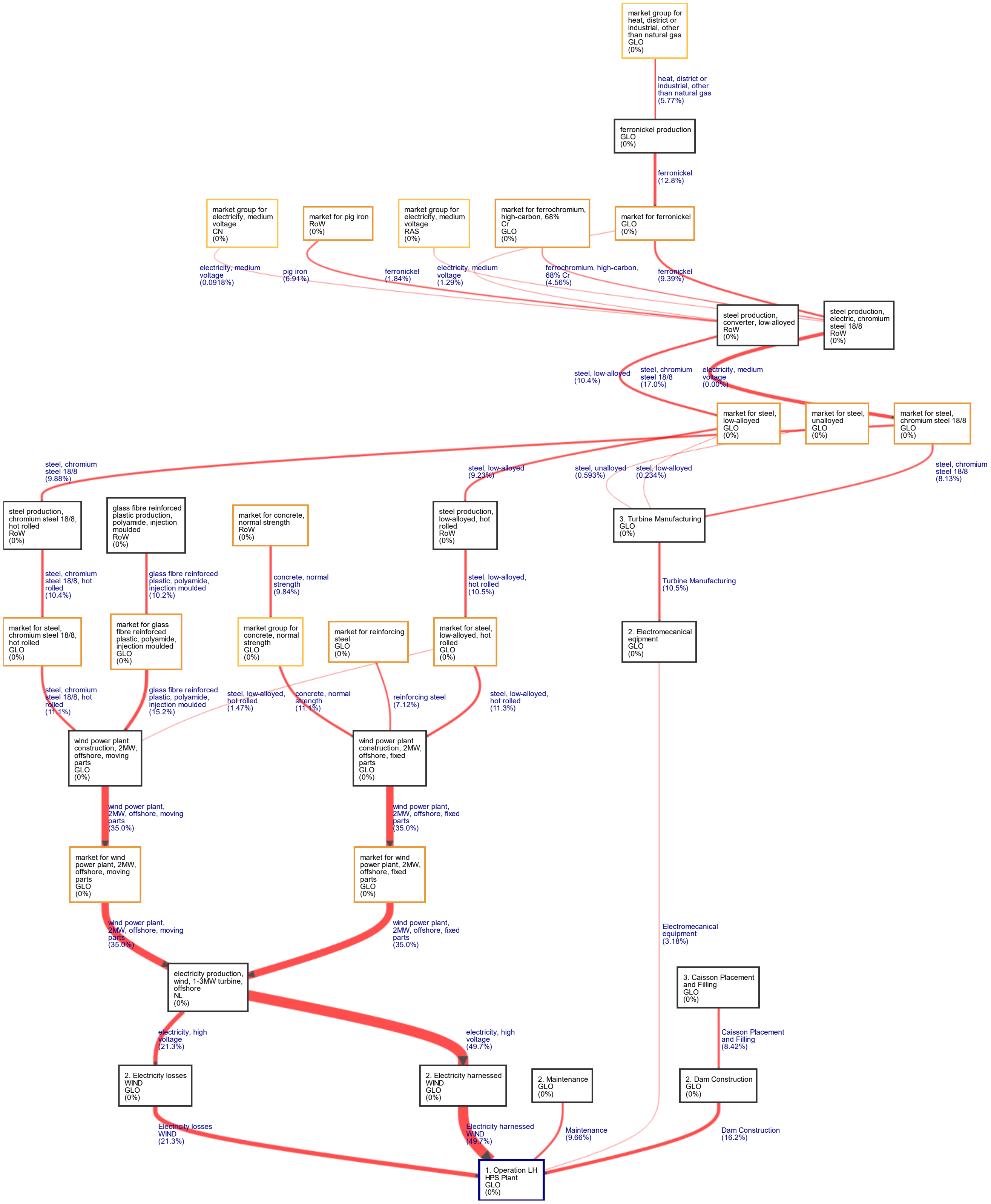


Figure S4. GWP Sankey diagram for the Wind scenario of LH PHS plant.

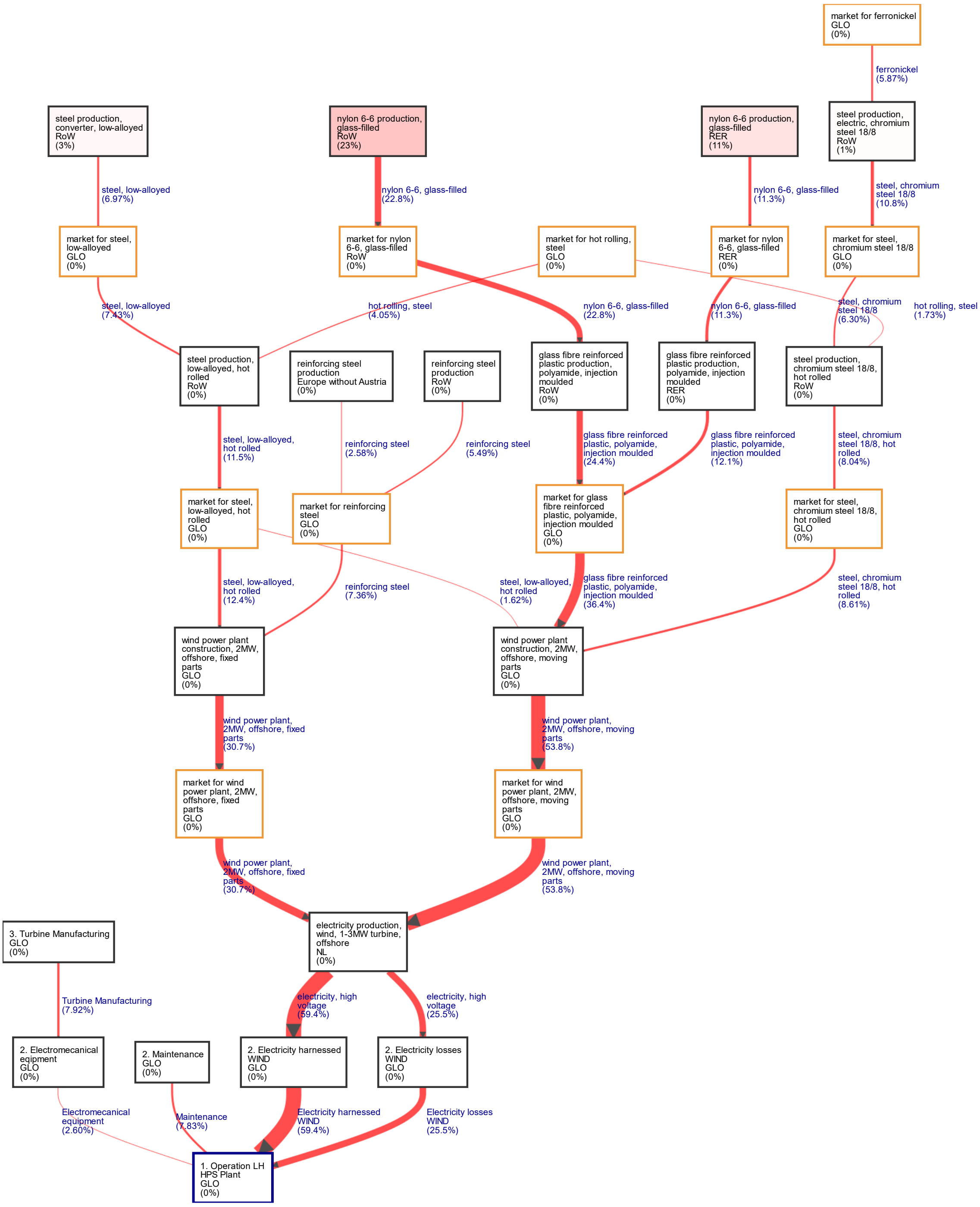


Figure S5. WUDP Sankey diagram for the Wind scenario of LH PHS plant.

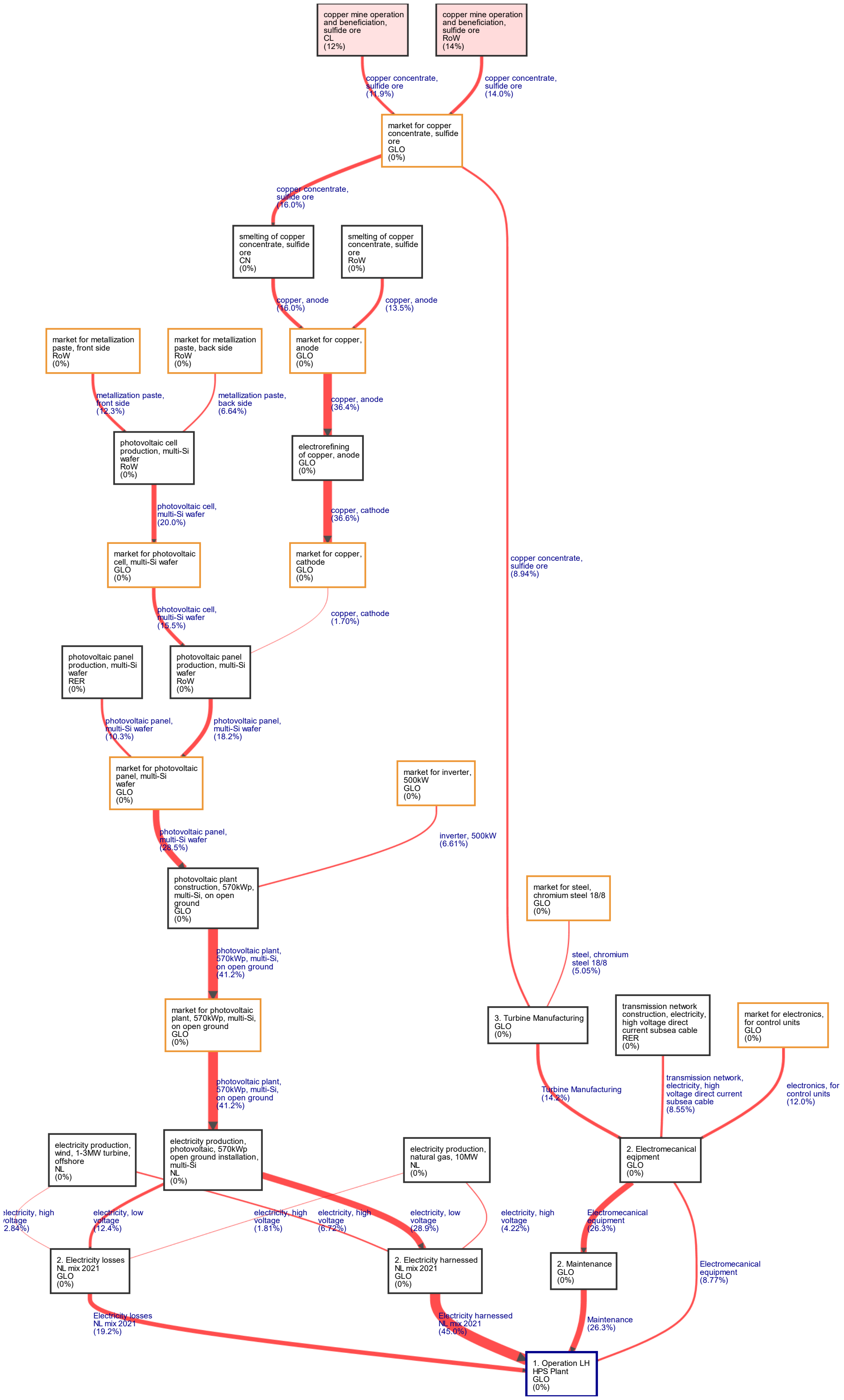


Figure S6. ADP-E Sankey diagram for the 2021 Dutch grid mix of LH PHS plant.

7.1.4.1 Technology Scenarios

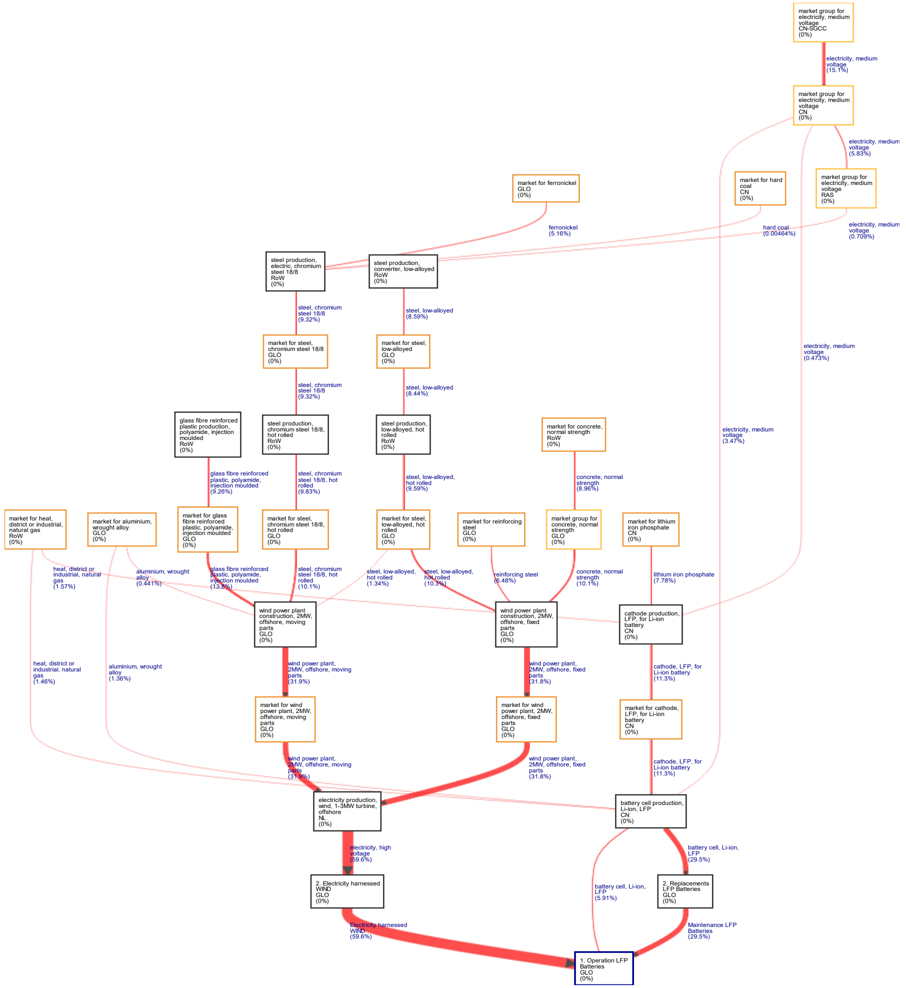


Figure S7. Complete Sankey diagram for GWP for LFP Batteries using wind electricity.

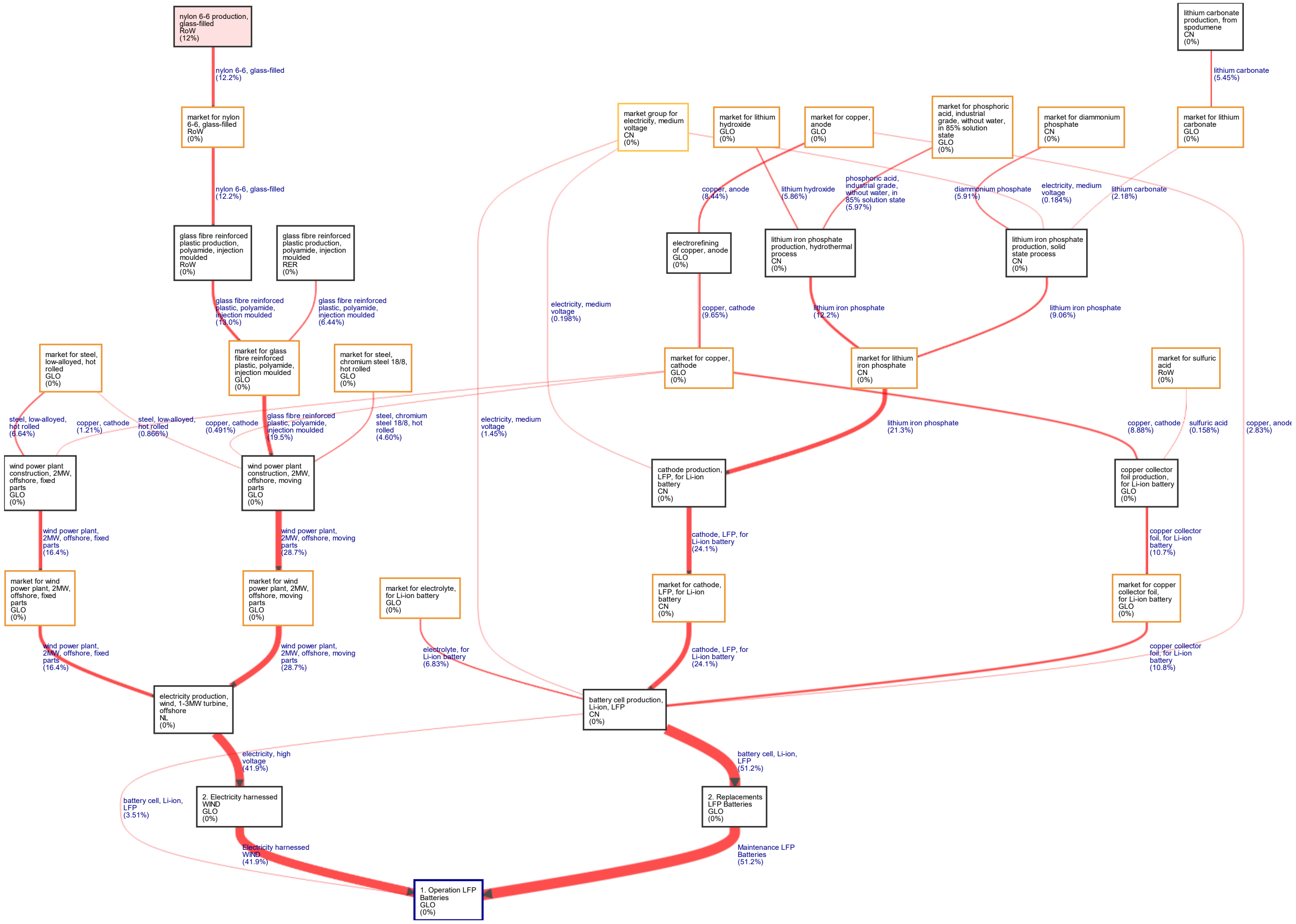


Figure S8. Complete Sankey diagram for WUDP for LFP Batteries using wind electricity.

7.1.5 Sensitivity analysis

7.1.5.1 Analysis 1. Dam lifetime

Table S3. Results for all category indicators estimated in this study for Sensibility Analysis 1.

Category Indicator	Scenario	LH PHS
GWP Global warming potential (kg CO2 Eq)	50Years	0.014817
	100Years - Baseline	0.009517
	125Years	0.008456
	200Years	0.006866
ODP Ozone depletion potential (kg CFC-11-Eq)	50Years	1.84E-10
	100Years - Baseline	1.3E-10
	125Years	1.19E-10
	200Years	1.02E-10
HTC Human toxicity: carcinogenic (CTUh)	50Years	8.29E-11
	100Years - Baseline	7.48E-11
	125Years	7.32E-11
	200Years	7.08E-11
HTNC Human toxicity: non-carcinogenic (CTUh)	50Years	2.86E-10
	100Years - Baseline	2.54E-10
	125Years	2.48E-10
	200Years	2.39E-10
PMF Particulate matter formation (disease incidence)	50Years	8.14E-10
	100Years - Baseline	5.66E-10
	125Years	5.16E-10
	200Years	4.41E-10
IR Ionising radiation (kBq U235-Eq)	50Years	0.000696
	100Years - Baseline	0.000629
	125Years	0.000616
	200Years	0.000596
POF Photochemical oxidant formation (kg NMVOC-Eq)	50Years	5.8E-05
	100Years - Baseline	3.8E-05
	125Years	3.4E-05
	200Years	2.8E-05
AE Acidification (mol H+-Eq)	50Years	0.000108
	100Years - Baseline	6.99E-05
	125Years	6.24E-05
	200Years	5.11E-05
ET Eutrophication: terrestrial (mol N-Eq)	50Years	0.000179
	100Years - Baseline	0.000117
	125Years	0.000105
	200Years	8.6E-05

EF Eutrophication: freshwater (kg P-Eq)	50Years	7E-06
	100Years - Baseline	5.06E-06
	125Years	4.67E-06
	200Years	4.09E-06
EM Eutrophication: marine (kg N-Eq)	50Years	1.81E-05
	100Years - Baseline	1.23E-05
	125Years	1.12E-05
	200Years	9.44E-06
EXF Ecotoxicity: freshwater (CTUe)	50Years	0.070533
	100Years - Baseline	0.061666
	125Years	0.059892
	200Years	0.057232
LU(Q) Land use, soil quality index (dimensionless)	50Years	0.047422
	100Years - Baseline	0.037477
	125Years	0.035487
	200Years	0.032504
WUDP Water use, user deprivation potential (m3 world eq deprived)	50Years	0.002697
	100Years - Baseline	0.002058
	125Years	0.00193
	200Years	0.001739
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	50Years	4.9E-07
	100Years - Baseline	4.8E-07
	125Years	4.78E-07
	200Years	4.75E-07
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	50Years	0.110322
	100Years - Baseline	0.082205
	125Years	0.076582
	200Years	0.068147

7.1.5.2 Analysis 2. Electromechanical equipment lifetime

Table S4. Results for all category indicators estimated in this study for Sensibility Analysis 2.

Category Indicators	Scenario	LH PHS
GWP Global warming potential (kg CO2 Eq)	20Years	0.010571
	25Years - Baseline	0.009517
	33Years	0.008463
ODP Ozone depletion potential (kg CFC-11-Eq)	20Years	1.48E-10
	25Years - Baseline	1.3E-10
	33Years	1.11E-10
HTC Human toxicity: carcinogenic (CTUh)	20Years	9.15E-11
	25Years - Baseline	7.48E-11
	33Years	5.81E-11
	20Years	3.1E-10

HTNC Human toxicity: non-carcinogenic (CTUh)	25Years - Baseline	2.54E-10
	33Years	1.99E-10
PMF Particulate matter formation (disease incidence)	20Years	6.45E-10
	25Years - Baseline	5.66E-10
	33Years	4.86E-10
IR Ionising radiation (kBq U235-Eq)	20Years	0.00077
	25Years - Baseline	0.000629
	33Years	0.000489
POF Photochemical oxidant formation (kg NMVOC-Eq)	20Years	4.26E-05
	25Years - Baseline	3.8E-05
	33Years	3.35E-05
AE Acidification (mol H+-Eq)	20Years	7.8E-05
	25Years - Baseline	6.99E-05
	33Years	6.19E-05
ET Eutrophication: terrestrial (mol N-Eq)	20Years	0.000131
	25Years - Baseline	0.000117
	33Years	0.000103
EF Eutrophication: freshwater (kg P-Eq)	20Years	5.84E-06
	25Years - Baseline	5.06E-06
	33Years	4.28E-06
EM Eutrophication: marine (kg N-Eq)	20Years	1.4E-05
	25Years - Baseline	1.23E-05
	33Years	1.07E-05
EXF Ecotoxicity: freshwater (CTUe)	20Years	0.074865
	25Years - Baseline	0.061666
	33Years	0.048466
LU(Q) Land use, soil quality index (dimensionless)	20Years	0.044359
	25Years - Baseline	0.037477
	33Years	0.030594
WUDP Water use, user deprivation potential (m3 world eq deprived)	20Years	0.002413
	25Years - Baseline	0.002058
	33Years	0.001703
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	20Years	5.98E-07
	25Years - Baseline	4.8E-07
	33Years	3.62E-07
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	20Years	0.095727
	25Years - Baseline	0.082205
	33Years	0.068683

7.1.5.3 Analysis 3. Reservoir capacity

Table S5. Results for all category indicators estimated in this study for Sensibility Analysis 3.

Category Indicator	Scenario	LH PHS
GWP Global warming potential (kg CO2 Eq)	16GWh	0.027979
	10GWh	0.030834
	8GWh - Baseline	0.032738
	4GWh	0.042254
ODP Ozone depletion potential (kg CFC-11-Eq)	16GWh	3.9E-10
	10GWh	4.29E-10
	8GWh - Baseline	4.55E-10
	4GWh	5.84E-10
HTC Human toxicity: carcinogenic (CTUh)	16GWh	1.95E-10
	10GWh	2.17E-10
	8GWh - Baseline	2.32E-10
	4GWh	3.07E-10
HTNC Human toxicity: non-carcinogenic (CTUh)	16GWh	1.19E-09
	10GWh	1.27E-09
	8GWh - Baseline	1.32E-09
	4GWh	1.58E-09
PMF Particulate matter formation (disease incidence)	16GWh	2.14E-09
	10GWh	2.3E-09
	8GWh - Baseline	2.42E-09
	4GWh	2.98E-09
IR Ionising radiation (kBq U235-Eq)	16GWh	0.001295
	10GWh	0.001484
	8GWh - Baseline	0.001609
	4GWh	0.002239
POF Photochemical oxidant formation (kg NMVOC-Eq)	16GWh	0.00012
	10GWh	0.000131
	8GWh - Baseline	0.000139
	4GWh	0.000177
AE Acidification (mol H+-Eq)	16GWh	0.000183
	10GWh	0.000204
	8GWh - Baseline	0.000218
	4GWh	0.000288
ET Eutrophication: terrestrial (mol N-Eq)	16GWh	0.000329
	10GWh	0.000364
	8GWh - Baseline	0.000388
	4GWh	0.000505
EF Eutrophication: freshwater (kg P-Eq)	16GWh	1.24E-05
	10GWh	1.39E-05
	8GWh - Baseline	1.49E-05

	4GWh	2E-05
EM Eutrophication: marine (kg N-Eq)	16GWh	3.55E-05
	10GWh	3.92E-05
	8GWh - Baseline	4.16E-05
	4GWh	5.4E-05
EXF Ecotoxicity: freshwater (CTUe)	16GWh	0.192469
	10GWh	0.210969
	8GWh - Baseline	0.223302
	4GWh	0.284968
LU(Q) Land use, soil quality index (dimensionless)	16GWh	0.111193
	10GWh	0.122436
	8GWh - Baseline	0.129931
	4GWh	0.167407
WUDP Water use, user deprivation potential (m3 world eq deprived)	16GWh	0.012567
	10GWh	0.013184
	8GWh - Baseline	0.013596
	4GWh	0.015654
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	16GWh	1.1E-06
	10GWh	1.24E-06
	8GWh - Baseline	1.34E-06
	4GWh	1.82E-06
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	16GWh	0.309282
	10GWh	0.333944
	8GWh - Baseline	0.350385
	4GWh	0.43259

7.1.5.4 Analysis 4. The Efficiency of the plant

Table S6. Results for all category indicators estimated in this study for Sensibility Analysis 1.

Category Indicators	Scenario	LH PHS
GWP Global warming potential (kg CO2 Eq)	Efficiency 60%	0.036608
	Efficiency 70% - Baseline	0.032738
	Efficiency 80%	0.029835
	Efficiency 90%	0.027578
	Efficiency 100%	0.025772
ODP Ozone depletion potential (kg CFC-11-Eq)	Efficiency 60%	5.09E-10
	Efficiency 70% - Baseline	4.55E-10
	Efficiency 80%	4.14E-10
	Efficiency 90%	3.82E-10

	Efficiency 100%	3.57E-10
HTC Human toxicity: carcinogenic (CTUh)	Efficiency 60%	2.59E-10
	Efficiency 70% - Baseline	2.32E-10
	Efficiency 80%	2.13E-10
	Efficiency 90%	1.97E-10
	Efficiency 100%	1.85E-10
HTNC Human toxicity: non-carcinogenic (CTUh)	Efficiency 60%	1.5E-09
	Efficiency 70% - Baseline	1.32E-09
	Efficiency 80%	1.19E-09
	Efficiency 90%	1.08E-09
	Efficiency 100%	1E-09
PMF Particulate matter formation (disease incidence)	Efficiency 60%	2.73E-09
	Efficiency 70% - Baseline	2.42E-09
	Efficiency 80%	2.19E-09
	Efficiency 90%	2.01E-09
	Efficiency 100%	1.86E-09
IR Ionising radiation (kBq U235-Eq)	Efficiency 60%	0.001773
	Efficiency 70% - Baseline	0.001609
	Efficiency 80%	0.001487
	Efficiency 90%	0.001392
	Efficiency 100%	0.001315
POF Photochemical oxidant formation (kg NMVOC-Eq)	Efficiency 60%	0.000156
	Efficiency 70% - Baseline	0.000139
	Efficiency 80%	0.000126
	Efficiency 90%	0.000117
	Efficiency 100%	0.000109
AE Acidification (mol H+-Eq)	Efficiency 60%	0.000243
	Efficiency 70% - Baseline	0.000218
	Efficiency 80%	0.0002
	Efficiency 90%	0.000185
	Efficiency 100%	0.000174
ET Eutrophication: terrestrial (mol N-Eq)	Efficiency 60%	0.000433
	Efficiency 70% - Baseline	0.000388
	Efficiency 80%	0.000354
	Efficiency 90%	0.000328
	Efficiency 100%	0.000307

EF Eutrophication: freshwater (kg P-Eq)	Efficiency 60%	1.66E-05
	Efficiency 70% - Baseline	1.49E-05
	Efficiency 80%	1.37E-05
	Efficiency 90%	1.27E-05
	Efficiency 100%	1.2E-05
EM Eutrophication: marine (kg N-Eq)	Efficiency 60%	4.65E-05
	Efficiency 70% - Baseline	4.16E-05
	Efficiency 80%	3.8E-05
	Efficiency 90%	3.51E-05
	Efficiency 100%	3.29E-05
EXF Ecotoxicity: freshwater (CTUe)	Efficiency 60%	0.250243
	Efficiency 70% - Baseline	0.223302
	Efficiency 80%	0.203099
	Efficiency 90%	0.187384
	Efficiency 100%	0.174812
LU(Q) Land use, soil quality index (dimensionless)	Efficiency 60%	0.145341
	Efficiency 70% - Baseline	0.129931
	Efficiency 80%	0.118375
	Efficiency 90%	0.109386
	Efficiency 100%	0.102195
WUDP Water use, user deprivation potential (m3 world eq deprived)	Efficiency 60%	0.015519
	Efficiency 70% - Baseline	0.013596
	Efficiency 80%	0.012154
	Efficiency 90%	0.011032
	Efficiency 100%	0.010135
ADP-E Abiotic depletion potential elements (kg Sb-Eq)	Efficiency 60%	1.48E-06
	Efficiency 70% - Baseline	1.34E-06
	Efficiency 80%	1.23E-06
	Efficiency 90%	1.15E-06
	Efficiency 100%	1.08E-06
ADP-F Abiotic depletion potential fossil fuels (MJ, net calorific value)	Efficiency 60%	0.395083
	Efficiency 70% - Baseline	0.350385
	Efficiency 80%	0.316864
	Efficiency 90%	0.290791
	Efficiency 100%	0.269932

7.2 Annex 2. LCA Calculations

Annex_LCA Calculations

7.3 Annex 3. Inventory database

Annex_Inventory database

7.4 Annex 4. Software model LCA from Activity Browser

Annex_LCA
model_LH PHS.bw2p

8 References-Annexes

THE EUROPEAN COMMISSION,. (2021). Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. In *OJ L* (Vol. 471). http://data.europa.eu/eli/reco/2021/2279/oj/eng