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Life cycle assessment of offshore low-head pumped hydro storage and its comparison with other energy storage technologies

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Abstract

Purpose Europe aims to decarbonize its economy by 2050, which implies a significant deployment of renewables and energy storage technologies. Offshore low-head pumped hydro storage (O-PHS) is presented as an alternative solution for coastal countries with shallow seas and flat topography as a technology for grid-scale energy storage.

Methods We conduct a Life Cycle Assessment (LCA) for the construction, operation, and maintenance stages of an O-PHS plant located in the North Sea, with a rated installed power of 2 GW and an average daily storage capacity of 8 GWh. We further compare O-PHS with conventional pumped hydro storage (C-PHS) in two inland European locations and lithium iron phosphate (LFP) batteries. Due to the location of the O-PHS plant, offshore wind electricity generation is assumed. Although the study focuses on climate change, the results for all 16 environmental impact categories of the European Product Environmental Footprint methodology are provided.

Results and discussion We find that the O-PHS plant's construction, maintenance, and operation emits around 33 gCO2eq/kWh. When comparing technologies, O-PHS greenhouse gas (GHG) emissions are slightly higher than C-PHS in the Alpine region and LFP batteries. In contrast, C-PHS results in the non-Alpine region are twice as high as the rest of the technology values. From these emissions, we see that the impacts related to electricity storage are roughly the same as those related to electricity generation. In other words, the use of O-PHS technology doubles the emissions from offshore wind farms. Although this may seem a high premium to pay, it becomes a relatively low value when comparing it to the GHG emissions from the electricity mix from surrounding countries like Germany or the Netherlands. On the other hand, the high demand for steel, copper, and magnets, together with efficiency losses, makes turbines a hotspot for the O-PHS plant in all environmental indicators.

Conclusion This article urges engineers working in the O-PHS technology to focus on the turbines, increasing efficiency and considering circularity strategies during the design phase, including lifetime extension and recycling to reduce emissions across all impact categories.

Keywords Life Cycle Assessment · LCA · Low-Head Pumped Hydro Storage · Sustainability · Environmental impact · Energy storage · Hydropower · Batteries

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1 Introduction

Energy accounts for more than 75% of GHG emissions in Europe (CEU. Commu., 2019) and securing affordable and clean energy supply is of growing global interest (European Commission. Directorate General for Research and Innovation., 2021). Clean energy from renewable sources and the electrification of sectors currently dependent on fossil fuels are essential to reducing emissions. Energy storage is considered a critical technology for the energy transition due to the intermittency in electricity production from renewables and the asymmetry between electricity production and consumption (Hainsch et al. 2022; Rehman et al. 2015).

Among the different energy storage technologies, pumped hydro storage is a mature and well-established technology for large-scale energy storage (Blakers et al. 2021; Rehman et al. 2015). However, traditional hydropower plants rely on high elevation differences to function, making them unsuitable for regions with flat topography. Ongoing research explores the possibility of implementing offshore low-head pumped hydro storage (O-PHS) as a viable solution (Ansorena Ruiz et al. 2022; Hoffstaedt et al. 2022). This technology works on the same principle as conventional pumped hydro storage (C-PHS), where height differences between two separated water bodies provide energy for turbines to spin and generate electricity and pump water upstream when there is excess electricity production. The novelty of O-PHS is that turbines operate with a height difference of 30 m or less between the two water bodies (Bricker et al. 2023). Consequently, O-PHS requires more significant amounts of water, and thus volume, than C-PHS for the same storage capacity. Therefore, a logical place to build this infrastructure is at sea, close to offshore wind farms.

Many studies have looked into the environmental performance of different storage technologies. However, to the best of our knowledge, the ecological footprint of O-PHS has not been previously investigated. This research aims to fill this gap by performing a Life Cycle Assessment (LCA) of this technology using a reference case in the North Sea. Additionally, it compares the environmental impacts of O-PHS with those of existing storage technologies, namely C-PHS and lithium iron phosphate (LFP) batteries.

2 Methods

2.1 Goal, scope and overall approach

Using LCA, we aim to estimate the environmental impacts of an O-PHS plant and to compare it with alternative technologies. Figure 1 depicts a cradle-to-gate approach with two functional units (FU). Firstly, the construction and maintenance of an O-PHS plant. Secondly, the delivery of 1 kWh of stored electricity with a daily delivery of 8 GWh for 20 years, including the operation of the previously accounted construction and maintenance. The latter has a broader system boundary since it also considers operation emissions from electricity production, storage, and delivery. We use this second FU to compare technologies, such as O-PHS, lithium iron phosphate (LFP) batteries, and C-PHS. For comparability purposes, the system boundaries considered for these technologies are the same as in the O-PHS plant. Also, we assume that electricity is sourced from offshore wind energy for all three alternatives. Finally, the end-of-life (EoL) stage is not considered for any of the technologies due to a lack of data in this respect; instead, possible environmental impacts from this life cycle stage are discussed qualitatively.

2.2 Inventory analysis

We used the following data sources for this research. Firstly, data for the design and construction of the O-PHS plant comes mainly from (ALPHEUS H2020 Project 2024a; Ansorena Ruiz et al. 2022; Prasasti et al. 2024) related to the ALPHEUS project.

Secondly, the ecoinvent 3.9.1 cut-off database (Wernet et al. 2016) was used as a background life cycle inventory (LCI) database to represent the materials and energy

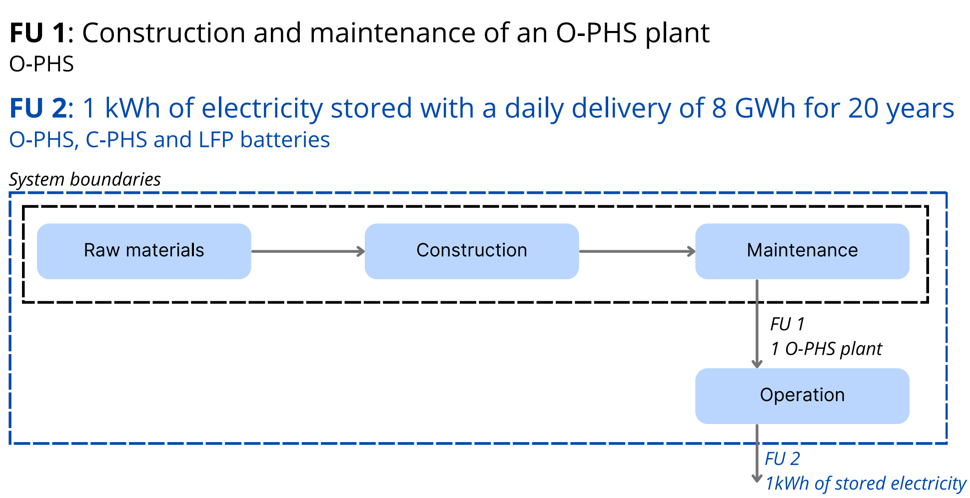


Fig. 1 Overall approach with the main sections of the system modelled fall inside the system boundaries, whereas the EoL fall outside of them. The two system boundaries present different functional units (FU), the first one depicted in black, and the second in blue

consumption for the three technologies. LFP batteries and C-PHS are modelled using LCI data from ecoinvent. Thirdly, missing information was estimated using data from available literature sources, as indicated in the respective references.

2.2.1 Offshore Low-Head Pumped Hydro Storage

We assume the O-PHS plant is located in the North Sea, 45 km from the Dutch shores as shown in Fig. 2. The specific location was identified from (ALPHEUS H2020 Project 2024b) and also employed in Hoffstaedt et al. (2024), after considering a technically viable location within the Dutch exclusive economic area, i.e. the sea considered as Dutch territory which extends 200 nautical miles from the state's baseline, excluding spaces already devoted for other uses, such as navigation routes, offshore windfarms, military purposes, or environmental protection (ALPHEUS H2020 Project 2024b). Further, it considers future offshore wind projects surrounding the location, providing the electricity needed for its 2000 MW capacity. Nevertheless, by increasing the electric machines' power, the reservoir size could be reduced (Hoffstaedt et al. 2024). In fact, seven potential sites have been identified, 3 in the Netherlands, and 2 in both Germany and France (ALPHEUS H2020, 2024b).

We follow the design proposed by Prasasti et al. (2024) for the construction, based on building a circular wall with a diameter of 5 km. The essential elements that constitute the most relevant parts of the dam are the foundations, the caissons, the inner berm, and the protecting layer, as depicted in Fig. 2. The plant's Lifetime is 100 years, and all the infrastructure needed for its construction and maintenance is considered.

Construction The energy and material requirements for the extraction of resources, transportation, component manufacturing, and construction of the O-PHS plant form the construction stage. The life cycle inventory data, calculations, and assumptions are provided in the Supplementary Information.

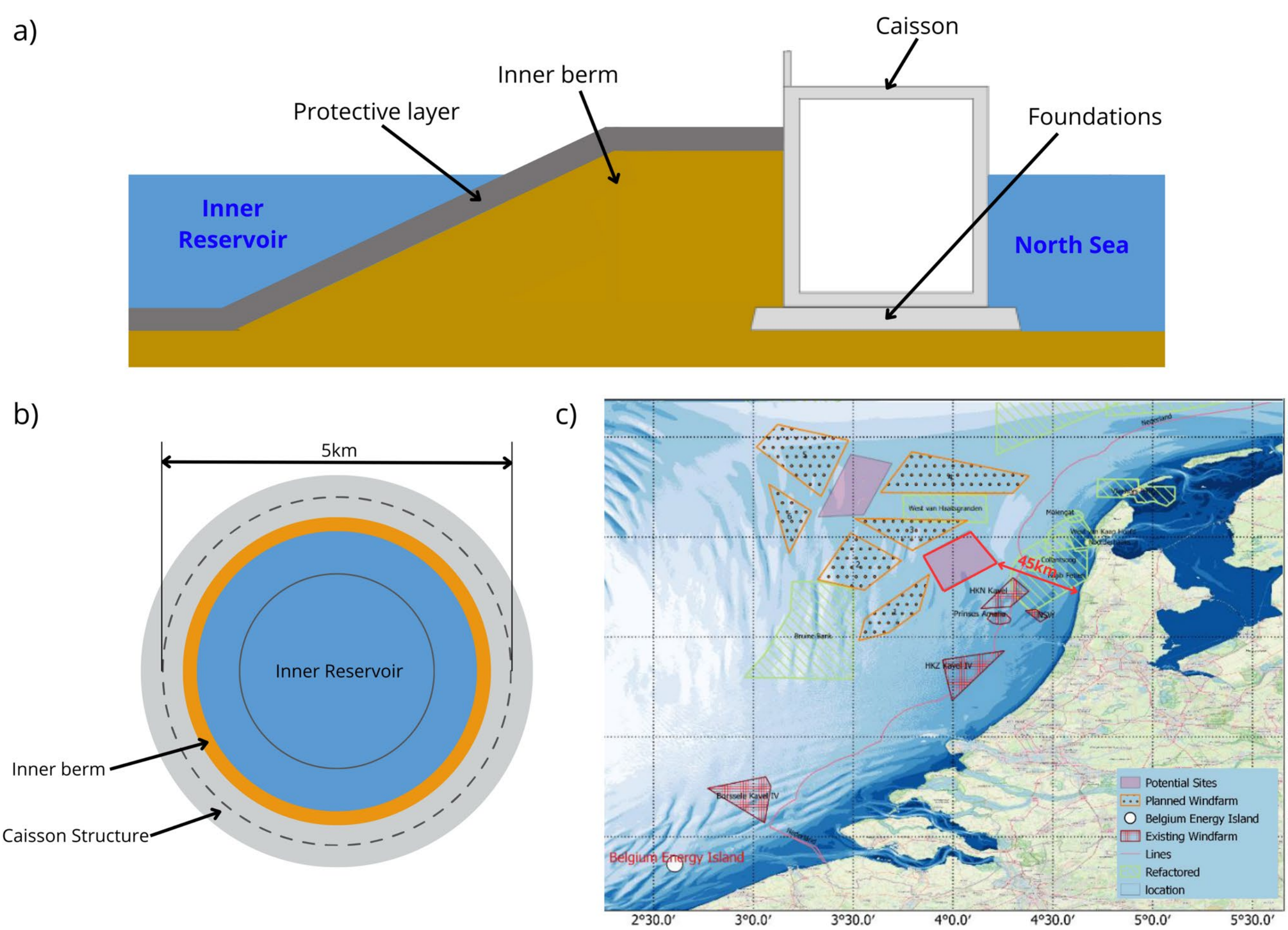


Fig. 2 O-PHS construction. **a** Transverse view of the dam with its different parts. **b** Top view of the dam with its diameter. **c** Highlighted as a red square, the project's geographical location is 45 km from the Dutch shores in the North Sea. Images retrieved from Alpheus Project's documentation (ALPHEUS H2020 Project 2024a, 2024b; Hoffstaedt et al. 2024)

Civil infrastructure Civil infrastructure refers to the non-moving parts of the construction, i.e. the dam. This structure is divided into four elements: the foundations, caissons, inner berm, and the protective layer. The foundations are made of granite and are modelled using data from Braga et al. (2017). Caissons are hollow rectangular blocks of reinforced concrete with dimensions 65.1 m long, 22 m wide, and 35 m tall. Once in place, they are filled with sand and are used to build the wall that separates the reservoir and the sea. The inner berm refers to the sand counterweight preventing the caissons from moving due to wave and current forces. All sand needed for this project is assumed to be taken from the inner reservoir's seabed, avoiding sand production on land and transport to the construction site.

A double layer of protection is considered to keep the inner berm's sand from excessive spilling: a filter layer composed of geotextile (Tencate 2019) and an armour layer made from granite rocks.

Electromechanical equipment Electromechanical equipment encompasses all machinery and components necessary for electricity conversion. Due to the extensive nature of this list, we focus on the most critical elements: reversible pump-turbines, power electronics, transformers, and subsea cables.

Counter-rotating pump turbines are considered a promising technology for O-PHS due to their efficiency in lower height differences (Ansorena Ruiz et al. 2022) and their dual ability to pump water up the reservoir and generate electricity. With an average round-trip efficiency of 70% (Fahlbeck et al. 2023; Prasasti et al. 2024; Truijen et al. 2024), the impacts of these turbines are estimated based on the material and energy inputs required for their manufacture. Electronics play an essential role in monitoring and controlling the machine. This study estimates the required amounts based on the turbine's weight. Literature consulted presents values from 0.59% to 1.32% of the total weight for turbines up to 2 MW (Alsaleh and Sattler 2019; Schmidt 2006). Considering that turbines in this study reach 10 MW, a conservative estimate of 2% of the total turbine weight is used to determine the electronics needed. Transformers are used to increase the voltage of a current to minimize transmission losses. An 880 MVA transformer is estimated to support a 2000 MW plant capacity (Molina Gómez et al. 2022). Using kg/MVA data (ABB 2003), the total weight of the transformer is calculated. Finally, 60 km of subsea cable is considered to ensure a safe range over the 45 km distance from shore.

Maintenance Maintenance is essential to ensure the long-term functionality of the infrastructure. For the dams' infrastructure operational and maintenance costs in standard PHS can go from 1 to 2.2% of the CAPEX (Connolly 2011; *Renewable Power Generation Costs in 2012*, 2013). Considering this, the assumption that the protective layer of granite will require 1% of the initial material for maintenance over the plant's Lifetime falls within that range. On the other hand, a more conservative approach is taken for sand losses, and for the inner berm, 10% of the initial sand requirements is considered for maintenance.

The electromechanical equipment has a Lifespan of 25 years, meaning all the equipment will be replaced three times during the 100-year operation of the plant. Additionally, lubricating oil usage is considered. Based on other studies, further, lubricating oil is considered and, based on other studies (Briones Hidrovo et al. 2017; Pang et al. 2015), it is observed that larger plants require less lubricant per MWh, resulting in a usage rate of 4.91e-6 kg/MWh. Maintenance and construction material requirements are summarized in Table 1.

Operation The machinery used for the operation of the plant results in emissions. Fugitive emissions of sulfur hexafluoride (SF6) from the cooling system and transformers amount to 3.4e-10 kg/kWh of electricity production (Verán-Leigh and Vázquez-Rowe 2019). Importantly, no biogenic emissions are considered for O-PHS, as these emissions, typically released from organic matter after flooding and drying the land, do not apply here due to the absence of such land changes associated with C-PHS plants (Gemechu and Kumar 2022; Pacca 2007). Figure 3 presents a simplified flowchart of the modeled Life Cycle Assessment (LCA) structure.

2.2.2 Conventional PHS

C-PHS is the technological parent of O-PHS. Their similarities make this comparison very relevant since C-PHS maturity can show O-PHS potential. C-PHS is modelled using the ecoinvent processes "electricity production, hydro, reservoir, alpine region" and "electricity production, hydro, reservoir, non-alpine region" (Wernet et al. 2016) with Norway and Germany as respective geographies. This is done following the reasoning that plants in these regions would be the closest alternative to the presented O-PHS. The main difference between these two processes is the amount of biogenic CO_2 eq emissions, defined directly by their location. These processes are selected because they consider all the infrastructure needed to produce 1 kWh from hydropower construction, operation, and maintenance. It is important to note that for these processes, the Lifetime of civil infrastructure is 150 years and 80 years for electromechanical equipment. Although this does not fit entirely with the model for O-PHS, it is considered the closest process from ecoinvent.

Table 1 Material requirements for the infrastructure of a 2 GW O-PHS plant. The percentage in the Maintenance column quantifies the amount of material needed to maintain the infrastructure compared with the initial construction amount

Infrastructure	Infrastructure sections	Major processes	Material needs (tonnes)	
			Construction	**Maintenance**
Civil infrastructure	Caisson	Reinforcing Steel	158,368	-
		Concrete CEM II/B-V	2,532,288	-
		Sand	18,561,067	-
	Foundations	Granite	12,119,007	-
	Protection Layer	Granite	12,563,323	125,633 (1%)
		Geotextile	3,411	-
	Inner Berm	Sand	104,141,023	10,414,102 (10%)
Electromechanical equipment	Turbine	Stainless Steel	157,072	471,216 (300%)
		Unalloyed Steel	31,554	94,662 (300%)
		Low Allowed Steel	11,326	33,978 (300%)
		Copper	11,326	33,978 (300%)
		Magnet	555	1,665 (300%)
	Electronics	Steel	487	1,461 (300%)
		Low Allowed Steel	487	1,461 (300%)
		Copper	29	87 (300%)
	Transformers	Steel	94	282 (300%)
		Low Allowed Steel	174	522 (300%)
		Copper	76	228 (300%)
	Sea cable	Low Allowed Steel	2112	6,336 (300%)
		Copper	847	2,541 (300%)
	General equipment	Lubricating oil	-	1,430

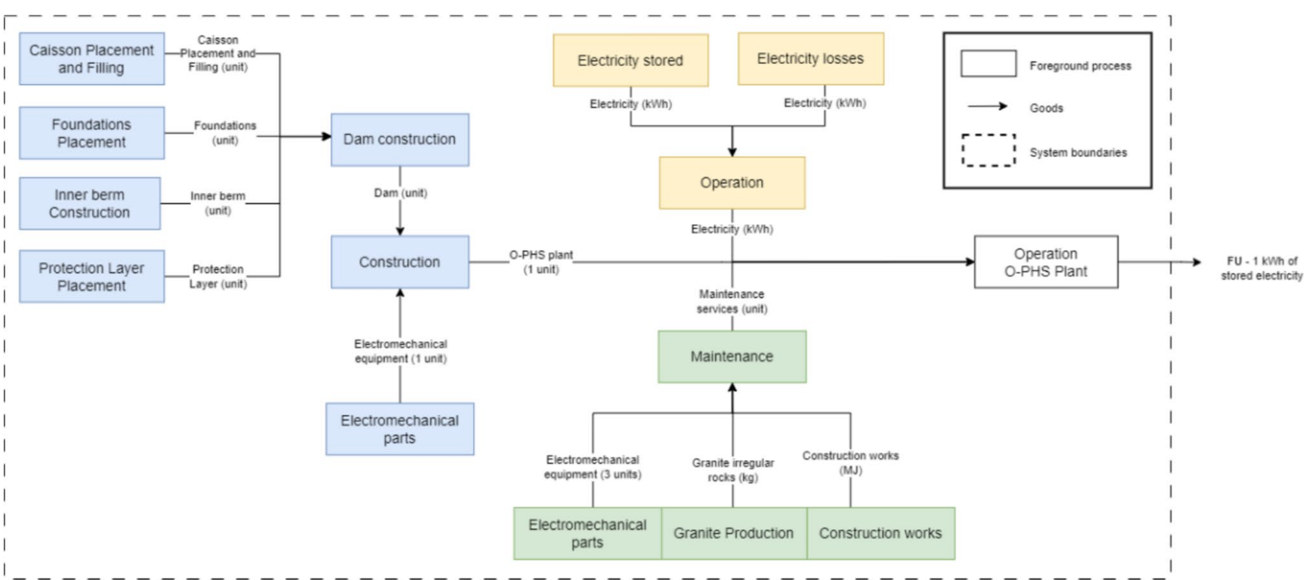


Fig. 3 A simplified flowchart was used in the O-PHS LCA model. Blue represents the construction, green represents the maintenance, and yellow represents the needed electricity. In practice, to model FU 1 (a single O-PHS plant), operation electricity is set to zero, and the electricity output is scaled to the total electricity output of the plant's life cycle

2.2.3 LFP batteries

From the many types of Li-ion batteries, LFP batteries are particularly suitable for grid storage applications and offer lower costs compared to other alternatives (Fan et al. 2020; Killer et al. 2020). Additionally, it is expected that battery manufacturers will shift away from utilizing conflictive materials such as cobalt. For these reasons, this study has chosen LFP batteries for comparison.

Following the recommendations of Arshad et al. (2022), all assumptions regarding battery Lifetime are clearly described to provide a comprehensive and transparent view of the model. It is assumed that the batteries will undergo a complete daily cycle, delivering the same amount of electricity as the O-PHS plant, 8 GWh per day. Accurately determining the Lifetime of a battery is challenging due to significant technological advances over the years and varying Literature values ranging from 1800 to 8000 cycles and from 5 to 20 years (Chen et al. 2012; Gallo et al. 2016; Lehtola and Zahedi 2019; Peters et al. 2017; Popp et al. 2014; Swierczynski et al. 2015). Furthermore, future technology developments may increase the lifetime of LFP batteries or result in new materials that outperform the assessed alternative. For this reason, we do not consider replacements once the lifetime of the LFP batteries is over. Based on the assumption that the battery conditions (material and operational) will be optimal, a Lifetime of 7300 cycles or 20 years has been selected.

The number of cycles a battery can undergo during its lifetime directly depends on the depth of discharge (DoD), which is the percentage of the battery that is regularly charged and discharged. To ensure a higher number of cycles and thus a longer lifespan, the DoD must also be optimal, though there is no consensus on the exact value. For electric vehicles (EVs), a DoD of 80% is commonly considered (Arshad et al. 2022; Peters et al. 2017), while some indications suggest that LFP batteries benefit from complete (100%) cycles (Spitthoff et al. 2020). Other research states that a DoD of 70% ensures the highest performance from lithium batteries (Park et al. 2023). This report adopts the most conservative approach, using a 70% DoD. This choice means that with 70% of the total capacity, the battery infrastructure must meet the O-PHS storage capacity, resulting in oversizing the number of batteries needed, directly affecting the infrastructure needs. Utilising LFP batteries' specific energy capacity of 0.159 kWh/kg (Dai et al. 2018), the total battery requirement is estimated at 71,878 tons for construction and 20 years of operation.

2.2.4 Electricity for storage and losses

Emissions from electricity production are highly dependent on the energy source and technology selection. The O-PHS plant analysed in this study aims to store electricity produced from offshore wind farms. Therefore, it is assumed that all the energy stored is sourced directly from offshore wind turbines. Similarly, storage technologies have inherent round-trip efficiencies, leading to a percentage of electricity being lost during the storing process. Such energy losses result in additional emissions associated with the energy required. To account for the storage efficiency in the model, the gross electricity inputs have been classified into the net energy delivered (i.e., the output of 1 kWh of stored electricity) and the energy losses (i.e., the additional electricity lost in the storage process).

For each technology, a range of average efficiency values is considered as a sensitivity analysis. The round-trip efficiencies for O-PHS are 65%, 70%, and 75%. For LFP batteries, Literature values range from 70 to 99% (Gallo et al. 2016; Killer et al. 2020; Peters et al. 2017). We use results from Peters et al. (2017), providing a range of 80% to 99%, with an average of 92.4%. For C-PHS, values of 65%, 76%, and 87% are used (Kougias and Szabó, 2017). Also, the lifespan of the different technologies has been varied ±10% as a sensitivity analysis. This will affect the final energy stored and delivered and is modelled through increasing or decreasing the electricity variables — i.e.: input, output, loses — while leaving the infrastructural needs the same. The best values regarding the efficiency and lifetime scenarios are combined into one scenario to model, and the same is done for the worst-case scenario.

2.3 Life Cycle Impact Assessment

Within the Product Environmental Footprint (PEF) methodology proposed by the European Commission (THE European Commission 2021), the Environmental Footprint (EF) 3.1 methodology provides a standard set of impact categories to assess with a specific characterization model. The assessed EF impact categories are Climate change (kg CO_2 eq), ozone depletion potential (kg CFC-11 eq), Human toxicity, cancer (CTU_h), Human toxicity non-cancer (CTU_h), Particulate matter (Disease incidence), Ionising radiation (kBq U235 eq), Photochemical ozone formation (kg NMVOC eq), Acidification (mol H + eq), Eutrophication terrestrial (mol N eq), Eutrophication freshwater (kg P eq), Eutrophication marine (kg N eq), Ecotoxicity freshwater (CTUe), Land use (dimensionless), Water use (m3 water eq of deprived water), Resource use minerals and metals (kg Sb eq), and lastly Resource use fossil (MJ).

The database from ecoinvent 3.9.1 cut-off (Wernet et al. 2016) feeds the modelling and calculations done through the open-source LCA software Activity Browser (Steubing et al. 2020).

3 Results

3.1 Environmental impacts of O-PHS

GHG emissions from the construction and maintenance of the O-PHS plant amount to 2,779 kt of CO_2 eq over 100 years. These emissions are broken down into different plant sections and material types in Fig. 4. The high amount of material requirements highlights the scale of the infrastructure, which is the primary contributor, accounting for 94.5% of the total climate emissions for this case study.

Civil infrastructure accounts for 55.7% of these emissions (1548 kt of CO_2 eq) while electromechanical equipment accounts for 44.1% (1,225 kt of CO_2 eq). Considering maintenance as the substitution of the electromechanical equipment once it reaches its EoL makes maintenance emissions three times higher than those of construction. The single largest emitter is the turbines, contributing 36.3% of the total emissions. Stainless steel, used in turbine manufacturing, is responsible for 28% of the overall GHG emissions. The caissons are another significant source, representing almost 29% of all emissions. This is divided between concrete CEM II/B-V (a type specifically used for marine constructions) at 11.8% and reinforcing steel at 17%. Lastly, granite, used for the foundations and protective layer, accounts for 21.6% of total CO_2 eq emissions, split into 10.6% and 11%, respectively.

One noteworthy material is sand, which is required in quantities exceeding 120 million tons. However, this sand is not produced but transported from the seabed and piled up to build the inner berm. Consequently, the inner berm has no emissions from sand production, only from the transportation process. Transportation-related emissions fall under 'Construction works' and account for 0.6% of total plant emissions. This mainly includes fuel consumption by ships used in various construction activities.

These absolute emissions can be translated into relative emissions by dividing the total number by the O-PHS plant's expected electricity, which results in 9.52 g of CO_2 eq/kWh for all the infrastructure. Emissions beyond GHG have also been analysed and categorised according to their origin to identify hotspots in the infrastructure. All impact categories listed in the LCIA part are quantified (per kWh) and depicted in Fig. 5. Despite the substantial dimensions of the dam—5 km in diameter and over 30 m tall—the emissions from electromechanical equipment exceed those from civil infrastructure in 12 out of the 16 impact categories. Furthermore, the contribution of civil infrastructure does not exceed 60% in any category, whereas electromechanical equipment accounts for over 60% in 8 impact categories and approximately 90% in 5. These findings highlight the

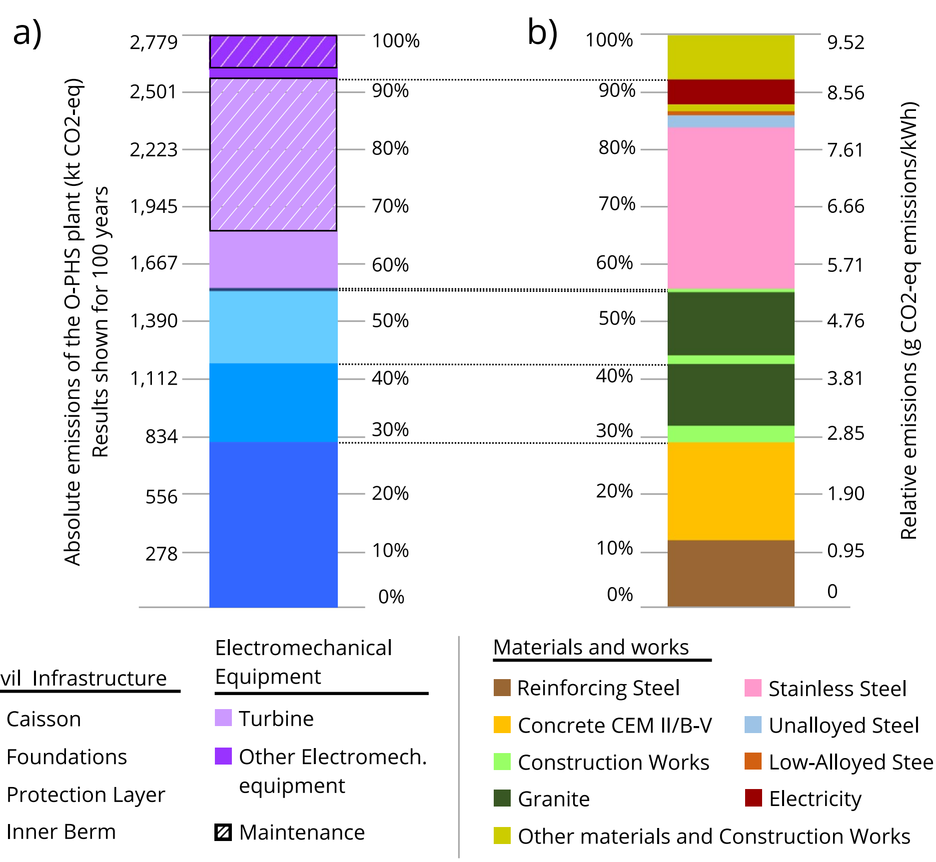


Fig. 4 Disaggregated absolute and relative GHG emissions from the O-PHS plant infrastructure. **a** Plant sections, construction in plain colour, and maintenance striped. **b** Materials and works used for the construction of the different sections. Between **a** and **b**, horizontal lines link the emissions from each plant section to the emissions of materials and works

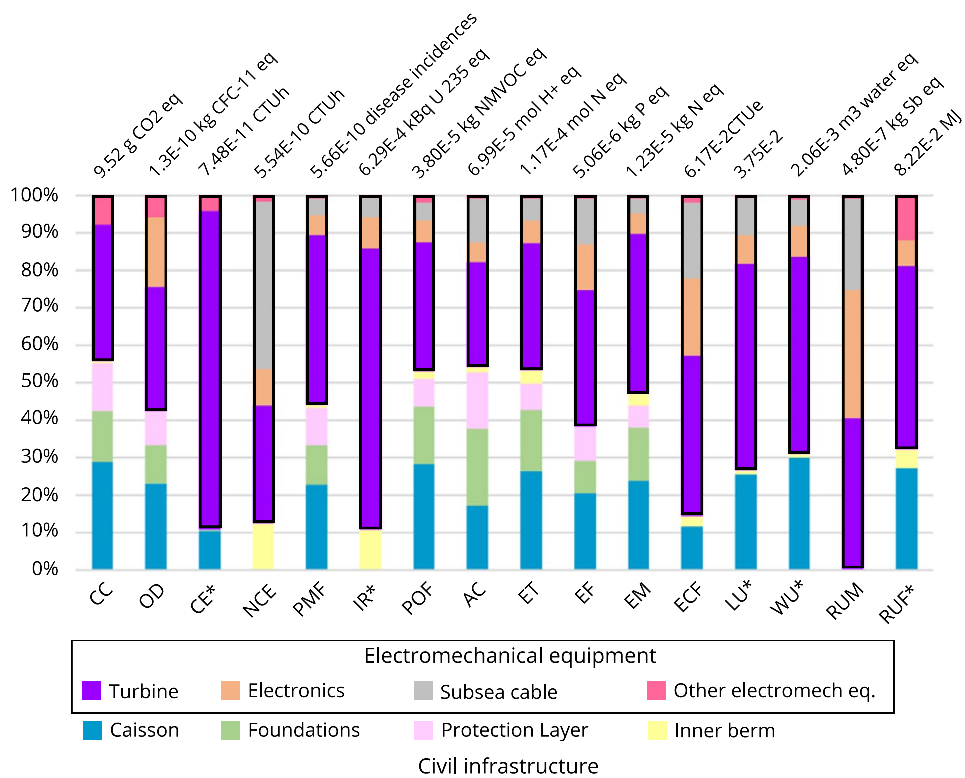


Fig. 5 Contribution analysis for the different sections of the O-PHS infrastructure with results for each category per kWh. The electromechanical footprint for each impact category is squared for easier identification. *Turbine's environmental footprint above 50%

Abbreviations stand for CC: Climate change; OD: Ozone depletion CE: Human toxicity: Carcinogenic; NCE: Human toxicity: Non-Carcinogenic; PMF: Particulate matter formation; IR: Ionizing radiation; POF: Photochemical oxidant formation; AC: Acidification; ET: Eutrophication-terrestrial; EF: Eutrophication-freshwater; electromechanical equipment: Eutrophication-marine; ECF: Ecotoxicity-freshwater; LU: Land use; WU: Water use; RUM: Resources use minerals and metals; RUF: Resource use Fossil fuels

significant impact of electromechanical equipment, particularly turbines, on the overall environmental footprint of the infrastructure. Turbines account for over 50% of the total emissions in five impact categories (see Fig. 5). In the acidification impact category, where turbines have their lowest contribution, they still represent an important role, accounting for 30% of the total impact. Therefore, mitigating emissions from turbines and their components stands out as an effective approach to addressing emissions across all impact categories in the infrastructure.

3.2 Comparison with alternative energy storage technologies

Factors such as electricity use, efficiency scenarios, and infrastructure emissions were considered together when comparing technologies. Overall, the GHG emissions of all technologies are approximately 30 g CO_2 eq, except for C-PHS non-Alpine, where biogenic emissions from the infrastructure increase the total to around 70 g CO_2 eq. Biogenic emissions are accounted for within the infrastructure block because they are the direct result of processes needed for the construction of a hydropower plant. GHG emissions from electricity delivered after storage are consistent across the four technologies, reflecting the footprint of 1 kWh produced by offshore wind turbines. These emissions from the electricity stored are the highest for three of the four technologies, reaching 16.25 g CO_2 eq/kWh. However, C-PHS non-Alpine diverges, presenting the highest emissions from storage infrastructure at around 50 g CO_2 eq/kWh. Despite variations in the type and quantity of materials used in their construction, the remaining technologies exhibit similar infrastructure emissions, ranging from 8.05 to 9.52 g CO_2 eq/kWh.

Emissions from electricity losses vary, considering the efficiency and the infrastructure Lifetime ranges defined in Section 2.2.4 for the different technologies. For O-PHS, emissions range from 5.42 to 8.75 g CO_2 eq (17.9%–24.6%); for C-PHS (Alpine and non-Alpine), they range from 2.43 to 8.755 g CO_2 eq (10.1%–30.2% and 3.8%–11.2%, respectively); and for LFP batteries, they range from 0.16 to 4.06 g CO_2 eq (0.6%–13.4%). This sensitivity analysis of efficiency and infrastructure lifetime is depicted by the error bars shown for each technology in Fig. 6.

When considering impact categories beyond climate change, the picture shifts (Fig. 7). The C-PHS results in Alpine and non-Alpine regions are nearly identical across the other assessed categories. LFP batteries are the highest emitters in 10 of the 16 categories, with copper and the cathodes' lithium-iron-phosphate being the primary contributors

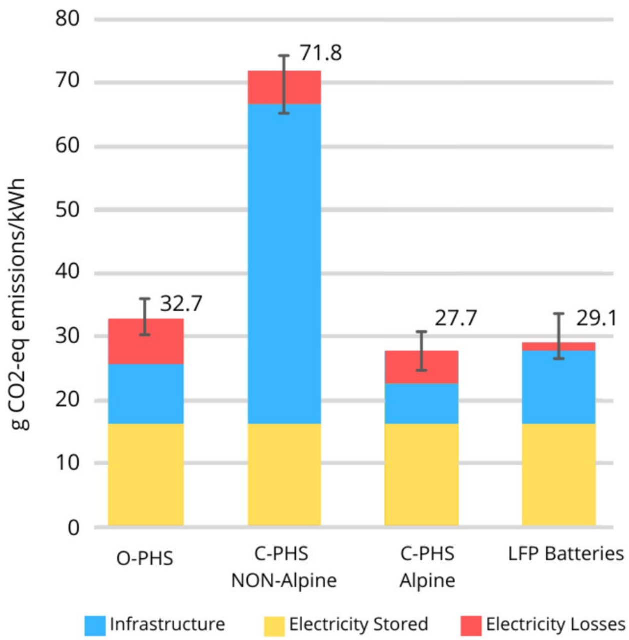


Fig. 6 GHG emissions from the three technologies analysed in this study. The source of the emissions is divided by the infrastructure: the material needs for the plant to work; energy delivered, the emissions associated with the production, storage, and delivery of 1 kWh; and energy losses, associated with the storage of 1 kWh

to these emissions. In contrast, O-PHS has the highest emissions in four impact categories, while C-PHS leads in two. Although impact categories are not directly comparable, these findings provide a broader environmental perspective. They suggest that O-PHS is a less polluting technology than LFP batteries in most assessed impact categories. Not only that, but it quantifies how less pollutant O-PHS is compared with LFP batteries.

4 Discussion

When comparing O-PHS with other technologies in this study, it can be seen that O-PHS results are in the same order of magnitude as LFP batteries and C-PHS. Moreover, there is no impact category in which O-PHS emissions disproportionally overshoot other technologies. Taking a closer look at the source of GHG emissions, we see that the production of electricity causes half of the emissions, while efficiency losses and the infrastructure account for 21% and 29% of the total emissions, respectively. This can be seen as an "environmental premium" to pay to store electricity; however, stationary batteries serve other purposes beyond storing energy. They also regulate the frequency in the grid and manage power(Bielewski et al. 2022), a task that is usually performed by thermal plants. In other words, the O-PHS plant not only would store energy, but would provide stability to the grid and therefore increase renewable penetration and reduce curtailment, dealing with the intermittency issues related to renewables. All this, at the relatively low cost of around 33 g of CO_2 eq/kWh, whereas the emissions of the countries surrounding the plant in 2023 (Netherlands, Germany, Denmark, and Belgium) went from 94 to 381 g of CO_2 eq/kWh (European Environmental Agency, 2024; Our World in Data, 2024).

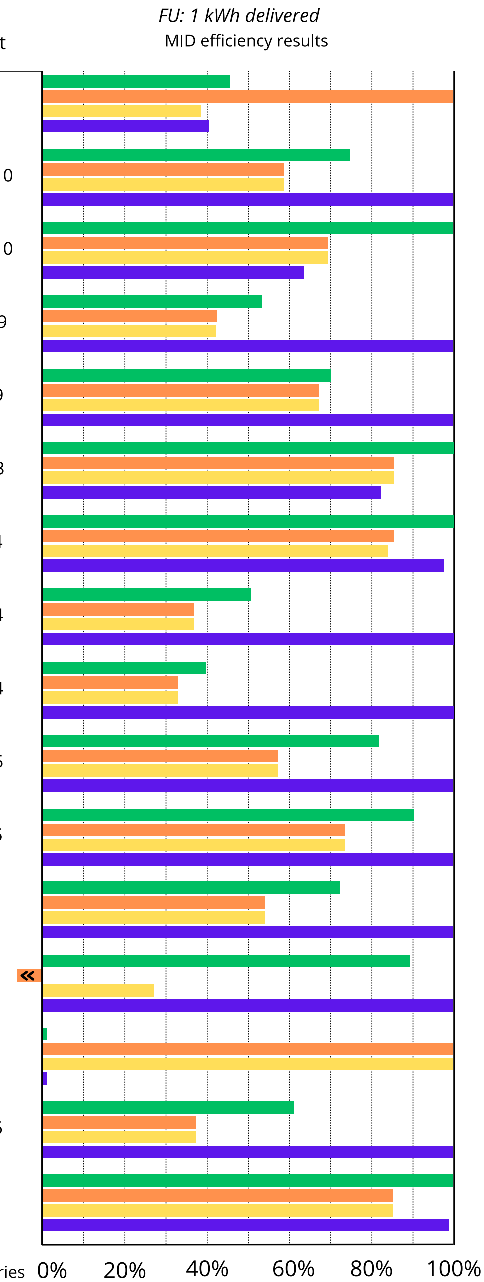
Nevertheless, seeing these optimistic results, we also compared our findings with results from the literature on different technologies. For this, we based the comparison on the literature review done by Rahman et al. (2015), which accounts for more technologies than those analysed in this study. We excluded results previous to 2015 and results with a different unit to g of CO_2 eq/kWh. Lead acid batteries, for example, present values ranging from 65 to 1157 g of CO_2 eq/kWh, while Li-ion batteries values range from 28–810 g of CO_2 eq/kWh, C-PHS results range from 8–276 g of CO_2 eq/kWh, and other alternative technologies Like compressed air energy storage and green hydrogen have results of 20–380 g of CO_2 eq/kWh and 386–700 g of CO_2 eq/kWh, respectively. This analysis shows that electricity-storing technologies, especially batteries, have a wide range of variability in the LCA results for GHG emissions. Considering these ranges, our results (28 and 29 g of CO_2 eq/kWh for C-PHS and LFP batteries) fall under the lower values range but are not outliers. When considering LFP infrastructure (Hiremath et al. 2015; Wang et al. 2018) find similar results as those in this study with 16 and 20 g of CO_2 eq/kWh, respectively.

However, we find three main reasons for these results to be at the low end of the ranges. First, different studies present their own assumptions and system boundaries that may differ. For example, Wang et al. (2018) consider 2000 cycles for the entire Lifetime of the LFP batteries and exclude the use phase, while in this study we consider 8000 cycles and include its use. Second, for C-PHS, biogenic emissions vary depending on the weather where the C-PHS plant is located, rising GHG emissions up to 547 g of CO_2 eq/kWh in tropical climates (Gemechu and Kumar 2022). Third and most importantly, in the referenced studies that consider the use phase (Abdon et al. 2017; Baumann et al. 2017; Hiremath et al. 2015) the electricity stored is from the grid from Germany, Switzerland, or the EU average. These GHG emissions per kWh surpass those from the infrastructure, going from 100 g of CO_2 eq/kWh in the Swiss case to more than 700 g of CO_2 eq/kWh in the German scenario.

This variance present in other technologies is important to give robustness to results. Thus, we believe that further research in O-PHS environmental assessment should be carried out to confirm the results presented in this study and to go into deeper detail on several key aspects of the O-PHS technology. Firstly, closer attention should be paid

Fig. 7 Results for the 16 impact categories included in PEF. Negative results are depicted with a shortened bar rather than its value in maintaining graphic aesthetics

	O-PHS	C-PHS Non Alp	C-PHS Alpine	LFP Bat
CC g CO2 eq	32.7	71.8	27.7	29.1
OD kg CFC-11 eq	4.55E-10	3.58E-10	3.58E-10	6.08E-10
CE CTUh	2.32E-10	1.62E-10	1.62E-10	1.48E-10
NCE CTUh	1.32E-9	1.05E-9	1.04E-9	2.47E-9
PMF disease incidence	2.42E-9	2.32E-9	2.32E-9	3.45E-9
IR kBq U235	1.61E-3	1.37E-3	1.37E-3	1.32E-3
POF kg NMVOC eq	1.39E-4	1.19E-4	1.17E-4	1.36E-4
AC mol H+ eq	2.18E-4	1.59E-4	1.59E-4	4.32E-4
ET mol N eq	3.88E-4	3.22E-4	3.22E-4	9.78E-4
EF kg P eq	1.49E-5	1.05E-5	1.05E-5	1.83E-5
EM kg N eq	4.16E-5	3.38E-5	3.38E-5	4.60E-5
ECF CTUe	0.223	0.167	0.167	0.308
LU (dimensionless)	0.130	-0.558	0.039	0.145
WU m3 water eq	0.014	1.267	1.267	0.014
RUM kg Sb eq	1.34E-6	8.18E-7	8.18E-7	2.19E-6
RUF MJ	0.350	0.299	0.299	0.347



Abbreviations stand for CC: Climate change; OD: Ozone depletion CE: Human toxicity: Carcinogenic; NCE: Human toxicity: Non-Carcinogenic; PMF: Particulate matter formation; IR: Ionizing radiation; POF: Photochemical oxidant formation; AC: Acidification; ET: Eutrophication-terrestrial; EF: Eutrophication-freshwater; electromechanical equipment: Eutrophication-marine; ECF: Ecotoxicity-freshwater; LU: Land use; WU: Water use; RUM: Resources use minerals and metals; RUF: Resource use Fossil fuels

to the circularity and EoL stage of the materials used, which stands out as a notable gap in most research, including this study. Considering the O-PHS plant is mainly made of steel, concrete, sand, and granite, returning these materials to the loop of economically valuable goods is already technically possible (de Andrade Salgado and de Andrade Silva 2022). Preventing equipment from becoming waste with designs that give higher importance to the EoL stage of the product has the potential to reduce the infrastructure's environmental footprint in virtually all impact categories. Strategies, including, but not limited to, repairing and remanufacturing the turbines, reusing the granite stones, or recycling the concrete and the steel from the caissons, can make a remarkable difference in the infrastructure footprint (Russell and Nasr 2023). However, although technological innovations are required to achieve this goal, the challenge is not only on the technical side.

Exploring business models and incentivising the economics of the activities involved in the recovery and circularization of material is paramount since the location and scale of the plant pose significant challenges for EoL and circularity strategies. In other words, although all these EoL strategies are already technically possible, this may not be economically feasible due to the magnitude and geographical situation of the materials. Therefore, more research in EoL strategies, scenarios, and alternatives for material circularity, waste management, and the decommissioning of the O-PHS plant is necessary in both the environmental and the economic spheres.

Secondly, the impact on the living organisms in the construction area and its surroundings is of the highest importance. This fact is not only relevant per se since the dam would create an artificial reef that could improve biodiversity in the area like offshore wind farms in the North Sea (Li et al. 2023) but also, it could potentially destroy all biodiversity in the construction area and surroundings during the construction process. Moreover, the decay of organic matter is precisely the main reason for biogenic emissions to appear in C-PHS. Depending on the location of the plant and the weather, this type of emissions can be the primary source of GHG emissions in the C-PHS technology (Gemechu and Kumar 2022). With this precedent and considering the scale of the O-PHS plant, we believe it is highly relevant to analyse the quantity and type of marine species that stay or pass through the area where the O-PHS plant is planned. More importantly, research should be carried out to study how the construction and operation of the O-PHS can affect them, if their decay in a closed area would result in biogenic emissions and if so, how high these emissions are.

5 Conclusions

Using LCA, we studied the environmental impacts of the emerging technology of Offshore Low-Head Pumped Hydro Storage (O-PHS). We find that the GHG emissions from an O-PHS plant are in the same order of magnitude as those from lithium iron phosphate (LFP) batteries and the best-performing Conventional Pumped Hydro Storage plants (C-PHS). Additionally, O-PHS results do not present disproportionate spikes in any impact category with respect to other technologies. On the contrary, LFP batteries present environmental hotspots for non-carcinogenic human toxicity, acidification, terrestrial eutrophication, and metal resource depletion; while water use is the most pressing issue for C-PHS. Despite further research needs, this highlights the potential of O-PHS as an alternative electricity storage technology from an ecological perspective. Also, from a scalability point of view, only in the North Sea, seven potential sites have been identified near the coasts of the Netherlands, Germany, and France (ALPHEUS H2020, 2024). In fact, smaller reservoirs are also possible options (Hoffstaedt et al. 2024). Although at this moment it is difficult to foresee with accuracy further potential sites for an O-PHS plant to be deployed, it could be argued that there are zones that already comply with some necessary requirements. The Yellow and the Baltic Sea comply with some of these requirements, such as having a relatively narrow sea bed and the presence, or foreseen presence, of offshore wind farms (4C Offshore, 2025).

Moreover, storing technologies like O-PHS not only store energy but also can provide ancillary services to the grid, such as frequency regulation, power management (Bielewski et al. 2022), and, in general, support grid stability. A stability that is crucial from a grid perspective as it deals with the intermittency of the renewables, increases their penetration, and reduces curtailments. With this context, the emissions from using an O-PHS plant to store energy and deliver it to the grid are about 33 g of CO_2 eq/kWh, while emissions from the plant itself (construction, maintenance and operation) result in 16.3 g of CO_2 eq/kWh. This means that there is a premium attached to the storage of electricity and providing the aforementioned services. A premium that is one-sixth of the current electricity mix of Denmark, the country with the cleanest mix in the region of the O-PHS plant from this study. While 50% of the emissions have their origin in the production of electricity from the offshore wind farms surrounding the O-PHS plant, the rest of the GHG arise from the construction and maintenance of the plant (29%) and from the wind energy that needs to be produced to compensate for the energy losses linked to the 70% roundtrip efficiency (21%). Among the infrastructure-related impacts, turbines account for around 32% of the total GHG emissions of the O-PHS plant, with 11% coming from the turbines' materials and 21% from the efficiency losses. Nevertheless, turbines are not only a major player in GHG emissions, but they are the major contributor in 15 of the 16 assessed impact categories when looking only at the infrastructure. Considering this, increasing turbine efficiency is paramount and should be prioritized to reduce the environmental footprint in all the impact categories. However, efficiency alone is not enough, as mining and refining materials, such as steel and copper, are highly polluting and energy-intensive processes. Therefore, all life-cycle phases of the turbines should be carefully considered for environmental improvements during the design stage. Future research should also consider the End-of-Life stage and the environmental gains that could be made through recycling. In addition, maximising the turbines' lifetime through, e.g., enhanced maintenance, repairs, and remanufacturing may further lower their per kWh impact. Furthermore, the use of less environmentally impactful materials or alternative production methods should be explored to reduce emissions across all impact categories for O-PHS.

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Data availability Supplementary data to this article can be found online at (https://doi.org/10.1007/s11367-025-02538-4).

Declarations

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