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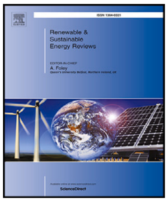

Low-head pumped hydro storage: A review on civil structure designs, legal and environmental aspects to make its realization feasible in seawater

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ABSTRACT

The energy transition requires large-scale storage to provide long-term supply and short-term grid stability. Though pumped hydro storage is widely used for this purpose, regions without natural topography do not have the potential for traditional high-head pumped hydro storage. To address this, multiple projects for low-head and seawater pumped hydro storage have been proposed, though few have been implemented. Here, we review the state of the art of the components of low-head seawater pumped hydro storage projects, for construction in shallow seas or integrated into coastal defenses. We reference all civil infrastructure components, in addition to legal, environmental/biological, and financial constraints, drawing knowledge from proposed, planned, and constructed tidal power and seawater pumped hydro storage projects worldwide. Combining this knowledge, we make a preliminary evaluation of the feasibility for low-head seawater pumped hydro storage in the North Sea. We find that an elevated storage basin is more economical than an excavated one in shallow bathymetry (10 m deep or less), while the reverse is true in deeper water. Corrosion and fouling prevention are already well developed due to implementation of these measures at tidal power plants. Dam construction is feasible if measures are taken to address piping, macro-instability (primarily from rapid drawdown), and bursting of the clay layer. Within the context of Europe, legal and environmental regulations may be the most formidable hurdles to such projects.

1. Introduction

Europe aspires to become the first climate-neutral continent in the world by 2050. Already by 2030, the European Union plans to reduce greenhouse emissions at least 55% below 1990 levels [1]. One of the targets defined to achieve this is to decarbonize the energy sector, i.e. introducing more renewable energy sources into the European grid. Currently, wind, solar, hydropower, solid biofuels, and other renewables are the main sources of renewable energy in the European grid, accounting respectively for 36%, 12%, 33%, 9%, and 9% of all the

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Abbreviations: CR, Counter-Rotating; PHS, Pumped Hydro Storage; RPT, Reversible Pump–Turbine; SPHS, Seawater Pumped Hydro Storage; TPP, Tidal Power Plant.; EU, European Union; FRP, Fiber Reinforced Plastic; GRP, Glass Reinforced Polyester; ESOI, Energy Storage On Investment; LCOS, Levelized Cost Of Storage; W, Watt (J/s); H, head (m); Q, volumetric flow rate (m^3/s); Rs, length of supercritical flow from breach (m); η_{gem}, average height of flood wave relative to original water level (m); a_0, average water depth during normal conditions (m); R, distance from breach (m)

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renewable energy generated [2]. During the period 2008–2018, wind power, solar power, and solid biofuels technologies have rapidly grown, making wind power the most important renewable source of energy in Europe [2].

The addition of large amounts of wind and solar energy to the grid, due to their stochastic and unpredictable nature, may drive an electric grid system to encounter transmission or operational constraints. At times of large wind and solar energy production, the system operators will have to accept less wind and solar than there is available (curtailment) [3]. The EU's Twenties project [4] showed with market simulations that wind curtailment might increase from 0.4 TWh in 2020 to 9.3 TWh in 2030, due to both increased energy generation and concentration of it at one geographical point.

Lack of transmission capacity is the main factor which governs curtailment, in the case where an excess of wind energy cannot be transported to other areas where it may be used [5]. Grid expansions are expensive and often time-consuming [6]. Energy storage is another option. Instead of taking the energy somewhere else it can be locally stored for later use [7]. Many studies show that wind and solar penetration in the electric grid can be increased with pumped hydro storage (PHS) systems [8–13].

PHS is a mature technology in mountainous regions and comprises 90% of the worlds grid-scale energy storage as of 2020 [14]. Chen et al. [15] showed that PHS technology ranks amongst the cheapest energy storage technologies in terms of costs per kWh of electricity stored and produced. PHS has several advantages, yet large head differences between reservoirs are typically required, rendering countries with lowland topography unsuitable. On a much lower scale of capacity, lithium-ion batteries have made rapid progress toward higher efficiency and lower initial costs, but their lifetime is much shorter and carbon footprint much greater than PHS. For example, Barnhart and Benson [16] showed that the Energy Storage on Investment (ESOI), which represents the ratio of total energy stored over a battery's lifetime to the energy required to fabricate the battery, is 32 for a lithium-ion battery, but over 700 for a PHS facility. Similarly, [17] shows that the Energy Capital Cost distributed over the lifetime of a lithium-ion battery ranges from $7.5-$104 per kWhr-cycle, while the cost of PHS is $0.02-$1.5 per kWhr-cycle. Therefore, development of PHS feasible for lowland countries would be beneficial for both the environment and the economy.

However, low-head PHS stations (see Fig. 1) are a new technology that have not yet been constructed. The objective of this manuscript is to gather knowledge from previous experience and plans for seawater hydropower (tidal power, high-head seawater PHS and low-head PHS) with the ultimate goal of finding suitable engineering techniques to make low-head PHS feasible. To achieve this, the authors used their expertise to gather information for each section that this manuscript presents. The research started by gathering experiences from operative tidal power stations, experience from the world's only seawater PHS plant (Yanburu SPHS) and plans for other seawater PHS and low-head seawater PHS plants. This research method is thus limited to the extent of information that the authors could access regarding the described topics. Literature about TPP and high head SPHS is widely available. However, information about low-head SPHS could only be gathered from projects planned in the past and ones being planned at present, as none have yet been built. The remainder of the work is organized as follows: we begin Section 2 with a historical introduction to seawater hydroelectricity. Section 3 focuses on technical aspects of dam construction and dredging processes, Section 4 on technical details for the construction of hydro powerhouses in seawater (special attention is paid to corrosion and fouling) and Section 5 deals with the state of the art of low-head reversible pump–turbine technology. Section 6 deals with environmental and legal aspects to be considered for the development of low-head PHS. In Section 7 an analysis of costs based on the reviewed literature is done. Section 8 discusses several topics that could lead to future research on low-head PHS. Finally, Section 9 concludes with the main findings from this review.

2. Past projects combining seawater and pumped hydro storage

We will begin our review by critically analyzing the interconnected lessons of PHS involving seawater. Seawater pumped hydro storage (SPHS) grows out of two existing technologies: high-head PHS and seawater tidal energy generation. High-head PHS encompasses 160 GW of installed capacity worldwide as of 2020 [14]. Its economical and ecological advantages warrant further research into PHS as a promising technology in appropriate settings. The International Hydropower Association estimates the installed capacity will increase to about 240 GW by 2030 [27].

2.1. Tidal power

SPHS for lowland countries can employ early knowledge from low-head tidal hydropower projects, since these have been operating hydroelectric equipment in seawater for several decades.

The La Rance tidal power plant (TPP) was the first modern TPP when its operation began in 1966, having an installed capacity of 240 MW. It is a 750 m long barrage that blocks the Rance River estuary at its narrowest point in St. Malo, forming a 22 km^2 basin [28]. The 1.7 MW TPP at Kislaya Guba (Kislogubsk), in experimental operation since 1968, was the first TPP to use floating caissons for the powerhouse construction in a narrow strait of 50 m width close to Ura Bay [29]. The Jiangxia TPP, currently the largest experimental TPP, started operating in 1980 and was integrated into a 670 m long existing rockfill dam [22]. The Annapolis TPP, the first TPP in Canada, was built in 1984. Its purpose was to demonstrate the commercial operation of a 7.6 m diameter straight-flow (Straflo) turbine. The choice of the turbine diameter for the Annapolis TPP was aligned with the turbine diameters used in the large-scale feasibility studies in Fundy Bay [30]. In 2011, the Sihwa TPP surpassed La Rance as the largest TPP with an installed capacity of 254 MW. A key aspect for the site identification of the Sihwa TPP was the possibility to flush the polluted Sihwa reservoir [31]. Characteristics of the above-mentioned TPP's are shown in Table 1. Meanwhile, many tidal sites worldwide have been investigated as possible TPP locations e.g. Severn (U.K.), Swansea Bay (U.K.), San Jose (Argentina) and Bay of Fundy (Canada). Efforts to improve existing TPPs are still ongoing. These early developments were usually based on topographic features, sometimes enhanced by civil works, to form specific TPP reservoirs for storage of potential energy supplied through tidal motions.

2.2. High-head seawater pumped hydro energy storage

By 1999, the Okinawa Yanbaru SPHS Power Station started operation and became the first PHS facility in the world to use seawater to store energy [32]. The installed capacity and storage capacity is shown in Table 2 together with the rest of the SPHS stations discussed in this section. The plant's cost was 30 billion Yen (around €232 million today) [33]. During the first five years of operation, the station was used as a research facility. Later, it provided electricity to Okinawa island until it was dismantled in 2016 because the energy demand on the island did not grow as expected at the beginning of the project [33]. Similarly to La Rance TPP, the acquired experience of Okinawa SPHS was a milestone for later plans.

Currently, several other projects have been planned but not constructed yet [10–12,34–37]. In Ireland, the Glinsk seawater pumped hydro was planned in 2012, involving a 960 MW station that could store up to 6 GWh per year. Its construction was planned to happen between 2014–2017 [38], yet not realized to date.

Several other plans have been developed for energy independence based on renewables in the Greek islands [10,34,35]. Katsaprakakis et al. [34] proposed two seawater pump hydro storage projects on the islands of Creta and Kasos. Partnering with the electrical contractor ENET S.A, they showed that installing wind parks together with SPHS

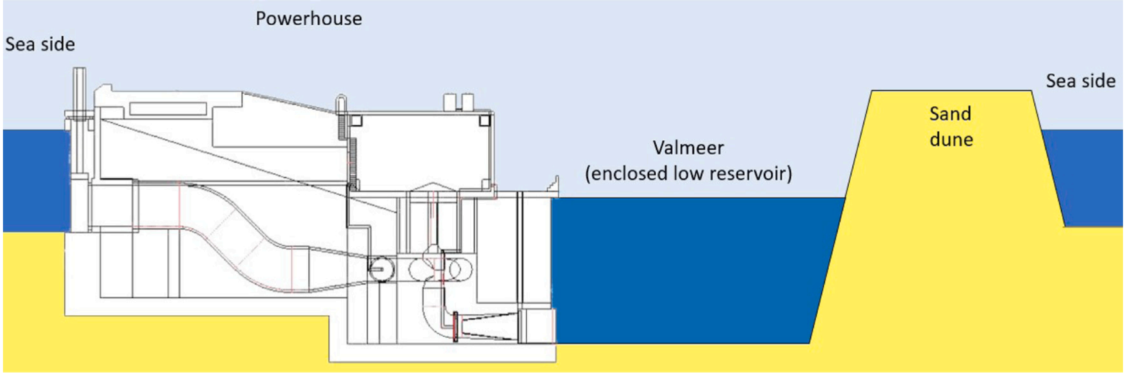

Fig. 1. Schematization of a low-head PHS scheme. Powerhouse conceptual design from: Ansorena 2020 [18]. Notice that the selected turbines are of the Francis type.

Table 1
Overview of relevant tidal power plants and their key features.

	La Rance	Kislaya Guba	Jiangxia	Annapolis	Sihwa
Location	France	Russia	China	Canada	South Korea
Area of reservoir (km^2)	22 [19]	1.1 [20]	1.5 [21]	6 [22]	42.44 [23]
Volume of reservoir (Mio. Mm^3)	184 [19]	–	5.14 [21]	–	147 [23]
Date of commissioning	1966	1968	1980	1984	2011
Operator	EDF	RusHydro	–	Nova Scotia Power Inc.	Kwater
Installed generator power (MW)	240 [19]	0.4 [20] after 2006: 1.7 [24]	4.1 [21]	20 [25]	254 [23]
Yearly energy output (GWh)	540 [19]	1 [20] after 2006: –	7.2 [21]	50 [25]	552 [23]
Mean tidal range (m)	8 [19]	2.4 [26]	5.08 [21]	6.5 [25]	5.6 [23]

Table 2
Characteristics of high-head seawater PHS projects reviewed. Notice that the upper reservoir of Kasos has a much larger storage capacity than necessary for daily storage. This is because of the topography of the island. The authors argue that this is an advantage for: (a) operation of the wind powered PHS for periods other than at peak power demand, (b) contribution of the wind powered PHS to controlling power production, and (c) improvement of the system's security.

PHS	Okinawa	Glinsk	Cultana	Rhodes	Crete	Kasos	Espejo de Tarapacá
Year of planning	1999	2012	2013	2014	2013	2013	2021
Installed power (MW)	30	960	225	160	64.5	4	300
Head difference, average (m)	142	292	260	270	500	472.5	604.75
Storage capacity (MWh)	188	6100	1770	1603	2346	516	35400

is a promising technology for insular systems with low annual rainfall [34]. On the island of Rhodes, a 150 MW plant could reduce the annual wind curtailment by 75% [10]. The most promising Greek case is the SPHS proposed for Sifnos island, which is planned to help achieve 100% local renewable energy generation together with an offshore wind park [35]. The project is currently looking for financing. In Australia the Cultana PHS project resulted from collaboration between the firm ARUP and the Australian Renewable Energy Agency. However, due to financial reasons, the plan did not go forward [39]. ARUP wanted to purchase the public land for installation of the plant but the Australian Government withheld permission [40]. Finally, in Chile the Espejo de Tarapacá project considers a 300 MW plant. Initially, the plan was to start construction in 2020. Currently, the plan is looking at finance methods and they aspire to have an operating plant by 2026 [41].

2.3. Low-head seawater pumped hydro energy storage

Low-head PHS is the most innovative SPHS technology and is necessary if PHS is to be feasible in countries without natural elevation differences available. Few plans have been developed so far, yet none have been constructed. In 1981, the Dutch engineer Luc Lievense published a proposal for an energy storage lake in the Markemeer (a large lake in the Netherlands) [42]. His plan involved the installation of wind turbines to pump water inside a 14 m high (relative to sea level) dyke ring. The water inside the ring would rise to 12 m above sea level and it would be turbined out of the basin when electricity is needed [43]. Afterwards, the plan developed into various alternatives at different Dutch locations such as the Haringvliet, Brouwersdam and the IJsselmeer. The final plan ended up with a 70 m high dyke alternative at the Brouwersdam [44]. Following the Lievense plan, in 2007 KEMA consulting and Lievense BV developed a new energy island design [45]. This design included a dredged 40 m deep basin [45] to be used as a low reservoir, with the sea as the upper basin. This 'bathtub' concept was named a 'valmeer', with the benefit of lower dykes avoiding safety concerns related to dyke breaching, which was a worry that plagued the 1981 plan.

In Taiwan, another design named TIESI (Taiwan Integrated Energy Storage Island) was developed in 2014. There, the water level inside the basin remains always below sea level just like the KEMA consulting plan. This plant considered the use of Francis turbines, which are a preferred option for all low-head PHS systems reviewed in this paper. However, Francis turbines are not ideal for low-head applications below 20 m (See Fig. 2), while axial Kaplan and propeller devices have not yet been optimized as reversible pump–turbines [46]. For instance, La Rance's axial Kaplan (bulb) reversible pump–turbines, designed by Neyrpic France in the 1960's, have a hydraulic efficiency for turbining and pumping of 85% and 65% respectively [47], leaving room for improvement.

In 2018, the Belgian Federal Government financed the planning of a multifunctional island (iLand) which includes the following functions: energy storage (low-head PHS), renewable energy generation

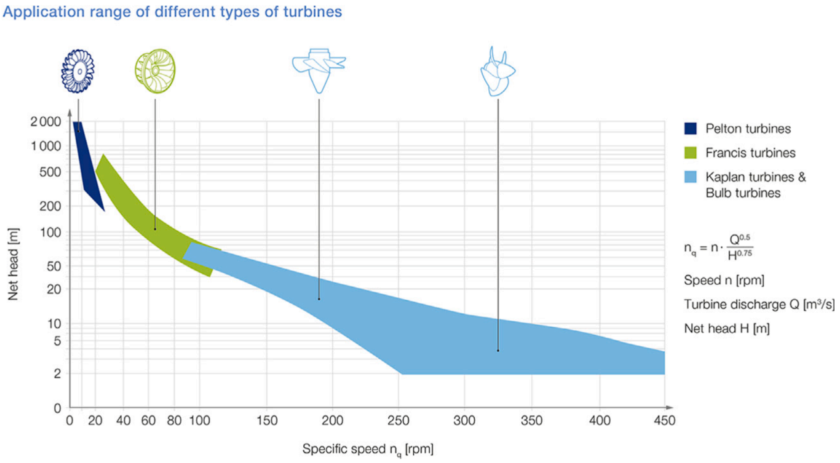

Fig. 2. Application range of Voith Hydro turbines.
Source: Voith GmbH webpage [56].

(installing new wind turbines and floating PV panels) and marine aquaculture. The plan's execution has been delayed due to permitting issues [48]. Since this would be the first cross-border hybrid storage project of its kind, negotiation with many different authorities is delaying the execution of this plan more than expected. Additionally, the regulatory framework concerning storage currently carries a rather large degree of uncertainty. It is expected that uncertainty will be reduced with the forthcoming adoption of the so-called "Clean Energy for all Europeans package" [48]. Some low-head PHS such as Delta21 [49] are integrated in the flood protection system of a country. Delta21 is an integrated plan for flood safety and energy storage in the area of the Haringvliet (South Holland, The Netherlands). Flood safety is provided by the construction of a new storm surge barrier and the use of a pumping station. The pumping station will be used to evacuate the river discharge during severe storms when the storm surge barriers are closed and river flow accumulates upstream of the barrier. To take advantage of the pumping station, a storage lake is constructed around it to have an energy storage basin which can be used daily. The Delta21 design considers 1920 MW of power with a storage capacity of 14.4 GWh. This project is currently studied on its feasibility. [18,50–55]. Table 3 shows the main characteristics of the analyzed low-head SPHS projects.

3. Dam design

This chapter elaborates on the characteristics of dam structures by first analyzing experience from tidal power construction to then continue with SPHS. For SPHS the main choice between a high or low reservoir is explained and the most critical failure mechanisms identified.

3.1. Tidal power

High-head PHS often uses Francis turbines for energy generation, but these are not designed for low-head operations (Fig. 2). In contrast, tidal energy stations obtain energy from low-head operation, thus being a reference for low-head seawater PHS.

3.1.1. Site characteristic and design

Potential TPP sites are examined by taking into consideration the average tidal range, the feasibility of the plant construction and the environmental impacts [22]. In addition, the design of a TPP depends on the purpose of the construction and potential secondary usage (e.g. road works). Therefore, the constructed TPPs have different scales. La Rance TPP operates on a commercial scale providing cost efficient energy for the bordering regions of the plant (1.8 € cents/kWh in 2009 [57]). Consequently, a large tidal range is essential for the La Rance site. The purpose for constructing Kislaya Guba TPP was to investigate the applicability of the floating powerhouse construction method on a large scale. Its location, even though it does not have a very large tidal range, was chosen due to the shape of the basin and the proximity to the grid [29]. The Annapolis TPP location at the mouth of the Annapolis river was selected mainly due to the existing causeway and sluice structure built in 1960 [30]. In addition, the existing tidal range in Annapolis was suitable for testing the application of a large diameter Straflo turbine [58]. Among the numerous small-scale TPPs in China, the Jiangxia TPP is the largest in operation. Most of the TPPs in China were decommissioned due to an inappropriate location and/or outdated technology [59]. However, the approach of small-scale TPP constructions in China was realistic and effective [60], contrary to the planned large-scale projects. In South Korea in 1994, a 12.6 km barrier was constructed to create the fresh water reservoir Lake Sihwa for providing irrigation water and additional land. Since the wastewater of nearby industry severely polluted the reservoir, the government later decided to enable water circulation between the reservoir and the sea and to simultaneously generate electricity [31].

3.1.2. Embankment construction

A TPP is generally composed of a powerhouse, a sluiceway, embankments and a navigation lock. A road is usually located on top of the dam to connect both ends of the estuary, providing added benefit to the overall plant. To date, all constructed TPPs follow the tidal barrage technique [61], which consists of closing the estuary at a narrow location with a powerhouse and an embankment. TPP designs are constrained by investment costs, which are strongly related to the chosen construction method [62]. At La Rance the main cost factor was the cofferdam construction [20]. The use of a cofferdam (dry construction method) was chosen for the dyke and powerhouse construction, to control high discharges during tides due to the closing of the bay [28]. The Kislaya Guba experience showed that the floating powerhouse construction method (wet construction method) can cut the cofferdam cost [20]. The floating method reduced the costs compared to conventional methods with cofferdams by one-third [63]. However, the floating method requires the preparation (dredging) of a channel, which can become expensive in shallow waters. In the Annapolis TPP, the rockfill causeway was already in place. The Annapolis TPP powerhouse was constructed on Hog's Island using the dry method. For Sihwa TPP, the integration of the powerhouse in the embankment dam was done using the dry construction method with a cofferdam and enclosure.

Sealing the embankment dam of the TPP is advantageous since it secures the construction and prevents head losses due to seepage.

Table 3
Characteristics of reviewed low-head PHS projects.

PHS	Lievense Plan	KEMA	TIESI	iLand	Delta21
Country	The Netherlands	The Netherlands	Taiwan	Belgium	The Netherlands
Year of planning	1986	2007	2014	2018	2021
Installed power (MW)	1500	1500	1500	550	1920
Storage Capacity (GWh)	30	20	20	2.2 (10 fn)	14.4

The 163 m long rockfill dam in La Rance has a concrete core for sealing, with an inspection gallery to measure deformations [64]. A rock revetment was placed for protection against wave and tidal actions. The Annapolis studies showed that allowing leakage through the existing causeway could significantly increase the costs of the project. Therefore, sealing of the causeway was carried out using the glacial till removed from the excavations on Hog's Island, allowing simultaneously the disposal of the till [58]. The dam in Jiangxia has a clay core for sealing purposes [21].

3.2. Low head pumped hydro storage

After a brief introduction to the key characteristics of offshore PHS this paragraph discusses the choice for creating an upper or lower inner reservoir supported by an economic analysis to determine what configurations of low-head seawater PHS are appropriate for various water depths. Furthermore the potential flood risk is discussed as well as construction materials, measures against seepage and the most important failure mechanisms.

3.2.1. Main characteristics of offshore PHS

A constructed (circular or otherwise enclosed) dam enables energy storage by controlling the water level of the inner reservoir and retaining a head difference between the out- and the inside. The energy storage capacity (E) of a PHS reservoir is determined by the head difference and the surface area (Eq. (1)). For a valmeer, the dam costs scale linearly with the circumference.

$$E = mgh = A\rho g \frac{H_{max}^2 - H_{min}^2}{2} \tag{1}$$

Where:

- E = Storage capacity (J)
- m = Mass of water (kg)
- g = Gravitational acceleration (m/s^2)
- h = Height difference (m)
- A = Area of the basin (m^2)
- ρ = Density of water (kg/m^3)
- H_{max} = Maximum head difference between upper and lower basin(m)
- H_{min} = Minimum head difference between upper and lower basin (m)

Therefore, the storage capacity scales with the diameter squared, whereas the circumference scales linearly with the diameter. Hence, the storage costs, €/GWh, decrease for a larger reservoir. Furthermore, the storage capacity scales with the head difference squared. To store a certain amount of energy a larger head difference results in a smaller reservoir diameter, which decreases the overall dam costs (not the dam costs per meter). This effect can be seen in Fig. 3. For the dam costs, the dimensions from Fig. 4 are used. The dredging costs are estimated at €8 /m^3 and the dredged volume is expected to be 1.4 times as large as the dam volume to account for spillage and settlement. Additionally, €60 /m^2 is considered for the dam footprint for drainage and soil preparation and €60.000/m for revetment costs per meter of dam length.

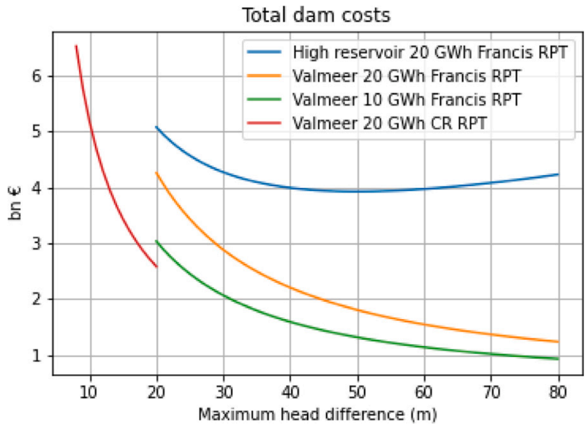

Fig. 3. Estimated total dam costs for seawater PHS, situated in 20 m deep water and equipped with bank protection to resist up to 8 m high waves (De Vilder, 2017). The calculations are done with the assumption that the Counter Rotating (CR) propeller reversible pump–turbine (RPT) operates down to an H_{min} of 2 m, while the Francis RPT operates from the shown maximum head difference down to a minimum head difference of $H_{max}/1.25$.

3.2.2. Upper or lower reservoir

The choice to use the sea as an upper versus a lower reservoir is straightforward for schemes that use the natural height difference along a coastline with cliffs. However, for offshore facilities both options can be considered. Studies by Lievense ended up with a preferred alternative that contained an inner reservoir that was 70 m higher than the sea level [44]. In 2007 KEMA and Lievense came up with the inverted process that would use the inner lake as the lower reservoir, called a 'valmeer' [45]. Since then all offshore studies have been based on the 'valmeer' principle, because it significantly reduces the dam volume [49,50,65].

3.2.2.1. Volume balance. As an example of the difference in dam volume, see Fig. 4. Both dams are able to store the same amount of energy, but the valmeer alternative only requires about $\frac{1}{3}$ of the dam volume. However, Fig. 4 does not show the amount of material that needs to be dredged for the valmeer. In case a 40 m head difference is created in 20 m deep water, roughly $400\,000\,000\,\mathrm{m}^3$ of material is leftover. In order to realize a feasible project it is therefore paramount to take the volume balance into account, to not end up with either a big deficit of construction material or surplus of dredge spoils. The relation between water depth, redundant material, storage capacity and maximum head difference is shown in Fig. 5.

The volume balance from Fig. 5 shows that for a certain water depth it is not feasible to construct a reservoir with any kind of storage capacity and head difference. From line 2 (orange) in Fig. 5 it can be deduced that for 10 m deep water a reservoir with 20 GWh of storage capacity and 20 m of maximum head difference results in almost 1×10^9 m^3 of excess material. In case the valmeer could be dredged for €8/m^3, this would lead to €8 Bn. of additional costs. In case a valmeer would be constructed offshore in combination with large-scale wind power development, it could be integrated with the creation of an 'energy island' for all the electric infrastructure and the operation and maintenance of the wind farms. Such an island could require 2×10^8 m^3

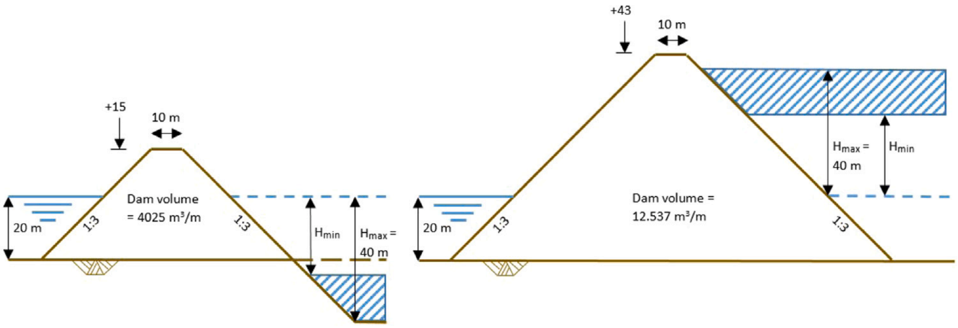

Fig. 4. The maximum water level difference (H_{max}) of 40 m is created for the valmeer (left) by dredging 20 m from the inner reservoir. The dam with the high inner reservoir (right) creates a 40 m head difference. The minimum head difference (H_{min}) is indicative and can change per turbine type.

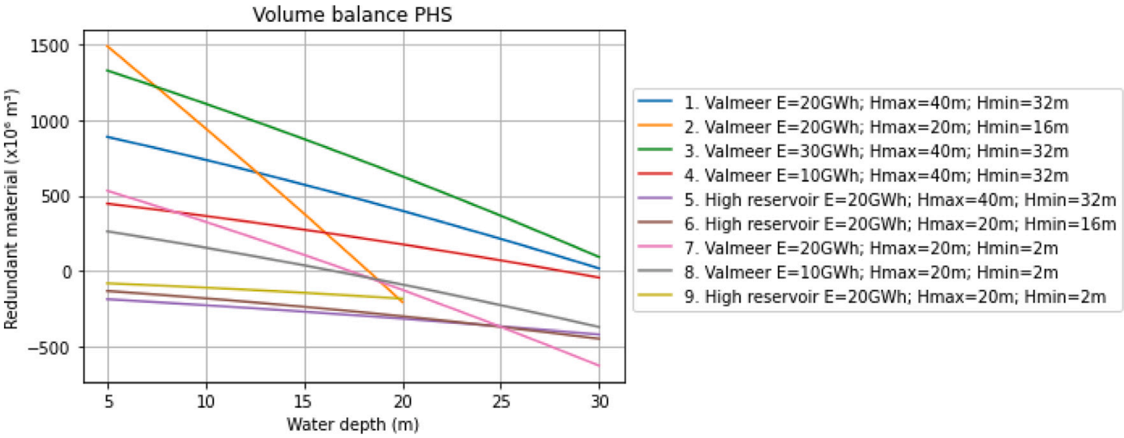

Fig. 5. The volume balance of both a valmeer and a high reservoir PHS facility for a given storage capacity (E) and head difference (H_{max} and H_{min}). Lines 1 to 6 use a Francis RPT and lines 7 to 9 use a CR RPT. The vertical axis shows the amount of redundant material, from which the dam volume is already extracted. Note that the dam is assumed to require 1.4 times its volume for dredging to account for spillage and settlement.

of sand [66], which can be sourced from the storage lake. Therefore in general a 'valmeer' type reservoir is more attractive for larger water depths (20 to 30 m) and a high reservoir in shallower water (5 to 10 m). Fig. 5 also shows that application of the CR RPT results in a broader water depth range in which the volume balance remains manageable than application of Francis turbines. This is caused because CR RPTs operate over a larger water level range at high efficiency, which reduces the reservoir surface area required to store the same amount of energy.

3.2.2.2. Flood risk. Aside from volumetric considerations, flood potential is another important aspect, as breaching of dam sections could pose a significant risk. Where a dam failure of a valmeer mainly incurs economic loss, a breach of a high reservoir could cause an extreme flood event, thereby requiring a higher design safety level than required for a valmeer. This effect is illustrated by the design failure probabilities that were calculated for high storage reservoirs near the Brouwersdam (integrated in coastline) and in the IJsselmeer (interior lake) [44].

For these 70 m high reservoirs, models show that the maximum outflow discharge could become 277 000 m^3/s (130 000 m^3/s and 99 000 m^3/s for 40 m and 24 m head difference respectively) in case of an instantaneous dam breach over the whole height of the dam and with a progressing breach width. From the breach a supercritical flow would develop that after a hydraulic jump transitions into a flood wave. The length of the supercritical flow and the average height of the flood wave are computed as follows:

$$R_s = \sqrt[5]{\frac{\left(\frac{Q_{max}}{\pi}\right)^2}{g f^3}} \tag{2}$$

$$\eta_{gem} = 0.55\frac{Q_{max}}{\sqrt{g a_0} R} \tag{3}$$

Where:

- R_s = Length of supercritical flow from breach (m)
- Q_{max} = Maximum discharge through breach (m^3/s)
- g = Gravitational acceleration (m/s^2)
- f = Coefficient for bottom friction: 0.004 (-)
- η_{gem} = Average height of flood wave relative to original water level (m)
- a_0 = Average water depth during normal conditions (m)
- R = Distance from breach (m)

This Brouwersdam scenario involved the failure of a protective dyke or dune subjected to the 1.7 km long supercritical flow [67]. The subsequent 7 m to 11 m high flood wave would evenly inundate the surrounding polders. Based on the inundation depth and the site's population, the expected death toll of a dam breach was estimated as 313 persons. Most casualties (244 persons) would occur due to the high speed of the supercritical flow, which was deemed 5 times as deadly as the subcritical portion of the flood wave. The total expected casualty rate led to a required design failure annual exceedance level of 10^{-4} or less. The same analysis for the IJsselmeer location resulted in a higher expected death toll of 3735 and a corresponding maximum allowable failure probability of 10^{-6} pear year, due to the deeper surrounding polder and denser population.

It was found that failure due to erosion of the dam crest due to overflow was the largest threat for the whole system [67]. This would be caused by a lack of control of the maximum upper water level. Consequently, it was suggested to use 2 or 3 independent monitoring systems to make the failure probability sufficiently small. Additionally, it was thought that for the coastal application of a high reservoir it could be socially beneficial to make the dam higher on the land-side so in case the dam would fail, it would likely flood towards the sea-side.

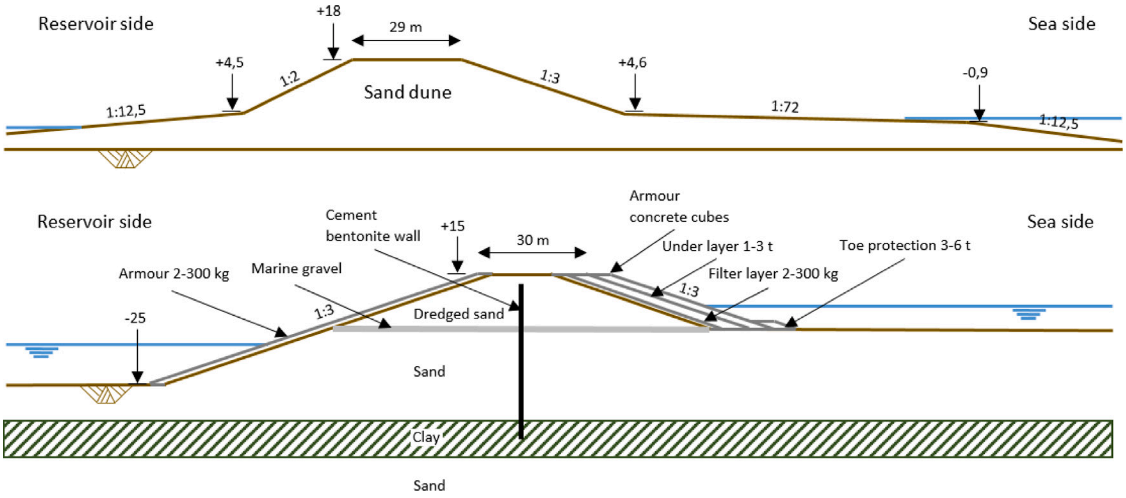

Fig. 6. On top, the dune design with a shallow foreshore from the valmeer project Delta21 that would be integrated into the coastline (modified from [72]). Below, the dam design for the offshore valmeer project iLand that uses hard armor protection and includes a cement–bentonite wall to limit seepage through the dam (modified from [65]).

The design failure probability of the valmeer that is considered for the Delta21 project would need to be at least 10^{-3} to be incorporated into the coastal flood protection network, to equal the failure probability of the current Haringvliet sluices that it would replace [68]. In general, an abrupt dam breach of a valmeer results in a negative flood wave [69,70], which due to the sudden drop in water pressure, could potentially cause outer slope stability failure of surrounding dykes. The added risk of inundation of a polder, caused by a dam breach that induces outer slope failure can be neglected. Consequently, it seems reasonable to assume that the risk of flooding caused by a valmeer's dam breach does not exceed the personal acceptable risk level in the Netherlands of 10^{-4}.

3.3. Dam structure

There is a large variation in the types of dam structures for low-head PHS projects, see Fig. 6. When there is no natural height difference available, some schemes use the existing coastline to reduce costs or offer additional services like flood protection [49]. All considered offshore dams use earth based designs, consisting of dredged material from the inner reservoir. For high reservoirs alternative designs were researched, using crown wall structures made of reinforced earth of roughly $\frac{1}{3}$ of the reservoir's height [71]. The use of a crown wall would significantly reduce the dam volume and could therefore save on the construction costs.

A low inner reservoir requires construction on top of a thick impermeable (clay) layer that prevents upburst and limits seepage through the bottom of the reservoir [45]. For the high inner reservoirs, considered in the Plan Lievense, seepage through the bottom was sufficiently reduced by depositing a 4 m thick and 200 m wide layer of marine silt at the inner toe of the dam [71]. Measures against seepage through the dam for low reservoirs consist out of bentonite walls [45]), sheet pile walls or impermeable cores [18,50,54] and for high reservoirs out of membranes and asphalt lining on the inner slope [36,37,71].

Protection against incident ocean waves is either provided by a dune profile [44,49] or a hard armor protection with appropriate freeboard as necessary to restrict wave overtopping [50,65]. The choice for hard or soft bank protection is not only based on economic aspects, but also on landscape and ecological integration as well as recreational aspects [71]. Therefore schemes that would be integrated in the coastline will likely present a dune profile while offshore alternatives will more likely contain rock or concrete armoring.

Failure mechanisms of a dam including instability, piping and liquefaction are considered manageable when adequately designed for [50, 67]. Van Adrichem [52] found that SPHS dam stability can be greatly affected by the rapid drawdown of the inner water level when the dam is saturated. He found that the slope of the Delta21 sand dune could be reduced to 1:5 and still be stable when considering several cycles of drawdown (17.5 meters of head drop/gain in 12 h). From the literature, it was found that stability during the construction process, dam settlement, and the constructability of dams in offshore conditions have not yet been investigated in detail. For the dam design of a valmeer special attention needs to be paid to the inner slope stability considering the uplift mechanism at the toe [50]. A distinctive mechanism that needs to be taken into account for a high reservoir near the coastline is salt intrusion, caused by 'far seepage' from the high water pressure inside the reservoir [44]. Overall no technical showstopper has been encountered for the dam construction.

4. Powerhouse and conveyance system

4.1. Powerhouse structure in tidal stations

Worldwide, TPP powerhouses have a similar structure, formed as a hollow concrete structure consisting of an upper and lower part. This structure can be referenced for low-head SPHS construction. The upper part mainly includes a maintenance hall with hoisting equipment. The lower part is laterally divided into subparts, each containing one turbine unit. Each turbine unit is connected to an inlet and a tailrace forming a straight waterway, which enables water passage in both directions with high efficiency. The flow is controlled by a wicket gate, a component of the turbine. To allow maintenance on the turbines and waterways under dry conditions, the powerhouse is equipped with a drainage system as well as gates or stop logs at the end of each inlet and tailrace. Since the waterways are not connected to each other, maintenance work can be done individually for each turbine and waterway.

Despite the similarities between the reviewed TPP powerhouses significant differences emerge from the powerhouse dimensions (Table 4), the waterway shapes, the placement of the turbine units within each powerhouse, and the concrete composition of the powerhouses. The differences among powerhouses are mainly due to the TPP capacity, the mode of operation, the highest tide level, the construction method, and the site conditions.

Table 4
TPP Powerhouse characteristics.

	La Rance	Kislaya Guba	Annapolis	Sihwa
Powerhouse Dimensions[a]: - Width[b] (m)	53.4 [73]	36 [74]	46.5 [30]	61.1 [23]
- Height[c] (m)	25 [73]	3.25 [74]	23 [30]	29 [23]
- Length (m)	390 [73]	18.3 [74]	25 [30]	380 [75]
Operating mode	Two-way generation	Two-way generation	Single-action, ebb generation	Single-action, flood generation
Construction Method	Dry	Wet	Dry	Dry
Number of Turbine(s)	24 units	2 units	1 unit	10 units

[a] Approximation.

[b] The start of the penstock to the end of the tailrace.

[c] Above the foundation level.

4.2. Construction methods for tidal power stations

TPP powerhouses are built either using the dry construction or wet construction method, depending on the site characteristics [76]. Dry construction methods require a cofferdam and consequent dewatering of the construction site, while the wet construction does not demand such requirements.

For the dry construction method cofferdams are constructed with different techniques. The cofferdams of La Rance TPP were built on the upstream and the downstream side using precast concrete caissons and sheet piles [73]. However, the cofferdam for the Sihwa TPP was built using long cylindrical cells, which are connected by spandrel walls [23]. The cofferdam for the Sihwa TPP was constructed only on the sea side, since the existing dam in Sihwa served as a cofferdam on the basin side. The dry construction of Annapolis TPP was less sophisticated, making use of Hog's Island at the mouth of the Annapolis River as a construction site. The powerhouse was constructed at Hog's Island by excavating a construction pit. The glacial till from the excavation was used to build the cofferdam on the upstream side of the island [25].

The construction of a TPP powerhouse in the dry is typically conducted according to the following steps: foundation preparation, powerhouse erection, and mechanical and electrical components installation. TPP powerhouses are generally made of concrete with high resistance against seawater [64,73,77]. In La Rance TPP, blast furnace cement (with 75% furnace slag) was used to increase the durability of the powerhouse [64]. The heavy components such as turbine units are installed using hoisting equipment. After the completion of the TPP powerhouse, the cofferdams are dismantled.

For the wet construction or floating method, the powerhouse is pre-fabricated and subsequently transported by water to the construction site. This method was used for the powerhouse of Kislaya Guba TPP [77]. In order to obtain reliable contact with the foundation, the bottom of the Kislaya Guba powerhouse was fitted with shear keys which were buried 25 cm deep in the sand layer [29].

4.3. Powerhouse structure in seawater pumped hydro and construction methods

High-head pump stations require the pump to be positioned deep below the lower reservoir water level in order to avoid cavitation. In Table 5 installation depths are shown. The high-head SPHS plant in Okinawa has an underground powerhouse, which can be accessed through a vertical shaft. This typical set-up was also proposed for Glinsk [37] and Espejo de Tarapacá [36]. For those projects, the powerhouse hosts reversible pump–turbines. In contrast, projects such as the Greek SPHS proposals consider the construction of separate stations for pumping and turbining [10,34,35]. According to the authors [10] this allows flexible operation which maximizes wind energy penetration and contributes to the system's stability and dynamic security. The total annual averaged efficiency of this system is 68.95% [34]. Both stations would be constructed at sufficient distance from the coastline to avoid direct contact with seawater [34] and excavation costs. The pumping units of the Greek SPHS schemes are considerably smaller than the rest and thus their required installation depth is also smaller (see Table 5).

In the Japanese SPHS project, a concrete tetrapod breakwater was constructed to protect the water intake. High wave energy in the proximity and minimal distortion to local water currents supported the construction of this structure. The Glinsk SPHS considered a similar design in which a tetrapod/Xbloc breakwater was considered both for protecting the inlet from the waves and currents and to dissipate the energy of the water entering the sea during the turbining operation [37]. For the Greek SPHS, the authors recommended building a submerged breakwater to avoid visual effects. The Espejo de Tarapacá seawater inlet has a diameter of 5 m which is covered by a 16 m diameter trash rack built of 1 cm bars with a spacing of 5 cm which aims to prevent large debris from entering the inlet pipe. Table 5 lists seawater intake depths ranging between 15–20 m for most projects proposed after Okinawa's plant due to the weak currents and insignificant wave motion at this depth.

The Lievense plan considered an in-situ built PHS station. The building pit was to be dredged to a depth of −25 m NAP (Normaal Amsterdams Peil). The dredged material is used to build the dyke of the building pit. Then, the building pit is drained and excavation works in the dry are carried out until reaching the level -40 m NAP. Finally, the powerhouse is built in the dry environment provided by the building pit. TIESI also considered the dry construction within a building pit for the PHS powerhouse construction. On the contrary, the iLand project considered modular construction with the use of prefabricated elements [45].

The Delta21 project studied several alternatives from in-situ built massive concrete structures to a modular prefabricated caisson structure positioned with the help of tugboats, considering the construction of a smaller PHS in combination with a sand dune [18,78]. Paasman and Ansorena [18,78] found that piping protection is important for the building pit construction, due to the difference in water head with both sides of the building pit's dyke. Piping solutions such as sheet-pile screens and the use of impermeable geotextiles, among others, are available.

An impermeable soil layer (e.g. clay) can affect the maximum excavation depth of a building pit or inner basin. When the clay layer is close to the surface, a sheet pile wall can be driven under the dam all the way down to the impermeable layer. This will restrict seepage into the reservoir and piping under the dam. However, the closer the impermeable layer to the surface, the shallower the maximum excavation depth becomes. This is due to the water pressures acting under the impermeable layer (See Fig. 7). Note that this upburst mechanism is also the limiting factor for the head difference inside a valmeer [18]. For a maximum excavation depth, the larger the pump–turbines, the lower the maximum water level difference available in the valmeer. Table 6 shows different submergence values for the pump–turbines considered by Ansorena (2020) [18] for the Delta21 powerhouse. Notice that the larger each pump–turbine unit, fewer units are needed to provide the desired power for a low-head SPHS plant, thus reducing the overall powerhouse width (material reduction).

Table 5
Characteristics of the intake pipe and submergence depth of the reversible pump–turbines in the high-head SPHS schemes analyzed.

	Kasos[a]	Rhodes[a]	Crete[a]	Curaçao	Okinawa	Espejo de Tarapacá	Cultana	Glinsk
Single pump/turbine power (MW)	0.560	1.074	1.162	19.8	30	100	117	300
Head difference (m)	472.5	270	500	–	142	604.75	260	292
Installation depth below sea level (m)	2	1	1	18–21	25	40–45	–	40-45
Intake pipe (seawater) length from coast (m)	635	20	400	–	27	340	–	–
Intake pipe (seawater) installation depth (m)	15	18	20	–	8	15.5	–	15-20

[a] Notice that the systems of Rhodes, Crete and Kasos consider separate structures for pumping and turbining. Therefore, for those cases the units are pumps instead of pump–turbines.

Table 6
Powerhouse dimensions and submergence for different pump–turbine characteristics. Submergence is defined as the depth from the lowest water level of the valmeer to the pump–turbine position.
Source: Ansorena (2020) [18].

–	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Pump discharge (m^3/s)	27	60	100	160	200
Pump power (MW)	5.0	11.1	18.5	29.6	37.0
Submergence (m)	2.4	3.6	4.7	5.9	6.6
Width estimation of Powerhouse[a] (m)	3320	2228	1722	1372	1218

[a] Based on the number of necessary pump–turbine units times the width of a single unit.

Note that these values are obtained for a head difference of 14 m, the average head difference of the Delta21 valmeer, which uses Francis pumps from Pentair/Nijhuis as reversible pump–turbines.

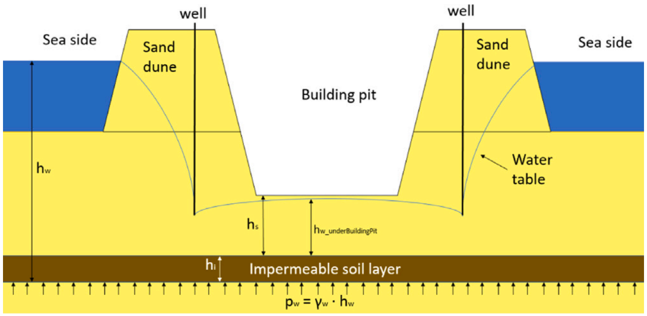

Fig. 7. Representation of soil upburst failure mechanism. When the water pressure under the impermeable soil layer is not countered by the weight of material and water above it, the water pressure will burst upward through the clay, causing failure of the building pit and its consequent flooding.

4.4. Corrosion prevention measures

A common corrosion prevention method used in most TPP powerhouses is active cathodic protection. In the La Rance TPP, in addition to stainless steel construction and painting of the turbine runners, active cathodic protection is used for the 24 turbine units, 6 sluice gates, and the metallic parts of the shipping lock. The electric power required for the supply of the active cathodic protection at La Rance TPP is 20 kW, with an annual consumption of 150,000 kWh [79]. In the Kislaya Guba TPP, the total power required for the active cathodic protection of the powerhouse is 3 kW, with annual consumption less than 12,000 kWh. Apart from active cathodic protection, stainless steel was also used in the Annapolis TPP for turbine blades and rotor rims [30]. Investigations after one year of operation (with 99% availability rate) showed minor spots of pitting corrosion on the runner hub. This demonstrates the effectiveness of active cathodic protection [25].

Corrosion prevention in Okinawa was different for components subjected to rapid vs. slow flow speeds [80]. Mild carbon steel coated with paint was used for the lower flow velocity regions whereas stainless steel was used for high flow velocity portions. Active cathodic protection was also used to prevent corrosion due to paint damage and against crevice corrosion. Since corrosion accelerates with higher flow velocities, the cathodic protection was designed with an adjustable protective electrical current. The wicket gate and runner were made of austenitic stainless steel with a low carbon content plus nitrogen, which was added to improve corrosion resistance. The main shaft – made of forged stainless steel – was equipped with a slip ring to provide the current cathodic protection. The draft tube was made of two different materials. The upper part was made out of austenitic stainless steel with a low carbon content whereas the remaining part was made of rolled steel which then was coated with a thick film of paint (vinyl-ester-like resin) containing glass flakes. Finally, the main shaft's sealing box was ceramic. In addition, the penstocks were made of Fiber Reinforced Plastic (FRP) with rubber joint seals, to avoid corrosion and to deal with the high flow speeds and pressures.

For relatively small diameters, [34] recommends the use of Glass Reinforced Polyester (GRP). The chemical structure of this material is inert to seawater. Moreover, its surface is smooth to reduce the head loss in the pipe system. It is both lighter and cheaper than steel, which also makes its installation simpler and thus cheaper. The drawback of this material is that the larger the pipe diameter, the lower the allowable internal water pressure. In the case of Kasos, a 0.8 m diameter pipe is considered. This limits the pressure to 32 bar [34]. In Crete, the diameter is 2 m and the maximum pressure drops to 10 bar [34]. GRP pipes can be combined with steel pipes if higher pressures are required. The interior of the steel pipe used in Kasos is covered with a thick film of mixed phenol and epoxy resins, without solvent [34].

Measures to avoid corrosion of the materials can be very expensive. The Australian seawater PHS system found that it was more profitable to build a desalination plant and use fresh water in the system than running it with seawater due to future maintenance costs [40]. The costs of constructing the water desalination plant plus the lower reservoir were lower than the costs of applying corrosion preventive measures over the lifetime of the structure.

4.5. Antifouling measures

Marine fouling, defined as the unwanted accumulation of marine organisms immersed in the sea [81], is an important factor both from economic [81,82] and environmental perspectives.

Fouling related problems generally occur in TPP powerhouses, causing deterioration of the structure and enabling settlement of organisms e.g. algae, mussels, which can partly clog the waterway. To prevent fouling, antifouling coatings and regular cleaning are used in all TPPs. [83,84] showed that fouled surfaces require recurring maintenance and cleaning activities, which constitute a relevant cost.

The Kislaya Guba TPP is equipped with an electrolysis unit to produce chlorine, which is used to keep aquatic microorganisms away from the waterway during breeding season. An investigation in 1998 stated

Table 7
Overview over available reversible pump–turbines (RPT)

	Axial flow pumps used as turbine (PAT)	Mixed flow PATs	Radial pump turbines	Archimedes screw	Positive displacement pump–turbine
Operative head range (m)	1–5 [94]	5–15 [94]	>60 [95]	2–10 [96–98]	–
Characteristics	Flow rates up to 1000 l/s. [94]	Flow rates of 50–150 l/s. [94]	Power usually exceeding 50 MW [95]	Discharge ranges up to 15 m^3/s. Low installation and maintenance costs, in turbine mode has been used with efficiencies up to 90% [99,100], but efficiency declines steeply with changes in water level [101]. Compared to conventional bladed pump–turbines, they are more fish friendly [97,99].	Low specific speed [102]. Tested as micro hydro turbines with pressures up to 5 bar (51 m) having efficiencies between 60%–80% [103,104]. Given their low speeds, they can be regarded as fish friendly [105]

that the electrolysis unit protected the waterway and the turbine from fouling for 20 years [85]. Additionally, the experience from Kinslaya shows that chlorine was not detected outside of the penstock [85].

However, according to the European Chemical Agency (ECHA), chlorine could be a threat to surrounding flora and fauna [86]. Furthermore, experience from Annapolis shows that the use of chloride in seawater caused deposition of manganese, which had to be scraped out every three to four years [87]. Nowadays the focus is on alternatives such as electrochemical degradation that minimize harm to the surrounding environment. This technology uses electric fields to kill fouling organisms directly, i.e. without producing a biocidal intermediate (such as chlorine) [88]. Furthermore, following the ban of environmentally harmful tributyltin (TBT)-based paints, the need for alternative technologies with comparable effectiveness and a lack of negative effects on aquatic flora and fauna is elevated.

In the case of SPHS, it is possible to hypothesize a future application of next generation antifouling technologies based on the use of natural biocides as additives to coatings [89,90], and other strategies such as the application of non-stick fouling release coatings [91] based on ultra-smooth surfaces.

5. Pump turbines

Conventional mountainous high-head PHS can operate at round trip efficiencies between 70% and 85% [92]. However, the pump–turbine units of these plants are not efficient for low-head applications (see Fig. 2). The available power (W) follows the following equation:

$$P = \rho \cdot g \cdot H \cdot Q \cdot \eta \tag{4}$$

where ρ is the density of the water (kg/m^3), g gravity acceleration (m/s^2), H head difference between basins (m), Q volumetric flow rate and (m^3/s), η the overall efficiency of a power plant (-). Eq. (4) shows that for low-heads, the volumetric flow rate must be increased to produce high power [93]. To limit system loss, for large discharges the diameter of the penstocks and pump–turbine runners must also be large (to keep flow velocity low).

As seen in Fig. 2, different kinds of turbines are optimized for different head and discharge ranges. In Table 7, different pump–turbines types suitable for low-head applications are shown.

Recently counter-rotating pump–turbines have been considered a promising technology for low-head PHS. Compared to conventional pump–turbines, the counter-rotating type can be of smaller size and have higher efficiency for a larger head range [106].

Having pump–turbines able to work at variable rotational speeds, allows for high efficiency and more power over a larger range of heads [107,108]. However, the costs of variable speed machines are around 30% higher than for fixed speed machines. Thus, the choice between each option relies on techno-economic and demand, [108,109] even though variable speed units ensure a higher renewable energy penetration [109].

For more information on pump–turbine preferences as well as other technological aspects (grid integration and electric machines and control) regarding low-head SPHS the reader is referred to Hoffstaedt et al.. 2022 [110].

6. Legal and environmental aspects

6.1. Legal aspects

As with any infrastructure project, PHS projects face legal and permitting tasks, whether on land or in the sea. To investigate the issues involved, we take as an example a hypothetical low-head PHS project located within waters subject to German administrative law, keeping in mind that other projects around the North or Baltic seas under other jurisdictions might face similar requirements, as the overall principles impacting the different national administrative laws are often similar.[1] Under the assumption that the plant will be entirely placed in the sea, the 1982 United Nations Convention on the Law of the Sea (UNCLOS) provides for – inter alia – two different regimes with different legal prerequisites:

1. The Exclusive Economic Zone (“EEZ ”) beyond the Territorial Sea and up to 200 nautical miles from the baseline (coast). This area does not belong to the adjacent state, which nevertheless can exercise certain rights regarding the use of this part of the sea and its natural resources. This zone plays an increasingly important role regarding the installation of electricity generating plants, as offshore windfarms nowadays are mostly installed farther away from the coastal area.
2. The Territorial Sea up to 12 nautical miles from the coast. In this zone, the adjacent state has full sovereignty.

Within the German EEZ in the North Sea or Baltic Sea, projects require permits from the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH), which enacts a single integrated permitting procedure that includes publication of planning documents and participation of all affected public and private

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[1] This chapter does not constitute and shall not be considered as specific legal advice.

stakeholders. The relevant law for construction in the EEZ is the Act governing plants in the EEA (SeeAnIG) [111]. Roughly summarized, the project permit might be granted if such construction does not endanger the maritime environment. Examples of harmful effects are seawater pollution, conflict with birds' migration routes, conflict with marine transport lanes, or conflicts with existing/ projected cables or converter stations (offshore windfarms). For the special case of a power plant not connected to the public power network or in case that the competent authority has set up special areas for "other energy generating plants", the Act regarding wind energy in the sea (WindSeeG) [112] providing for a tender procedure might apply. In either case, the crucial question will be to what extent the project will have a (negative) impact on the environment. Project owners will have to provide the authority with either a formalized environmental impact assessment ("EIA") according to the Federal Act governing the environmental impact assessment (UVPG) [113], or at least with an expert assessment regarding the potential impact on environmental aspects protected by the SeeAnlG.

Within the German EEZ, there are "Natura 2000" areas. The Council Directive on the conservation of natural habitats and of wild fauna and flora [114] and the Directive on the conservation of wild birds [115] was transferred into national law by integrating its provisions into the Act regarding the protection of the environment (BNatSchG) [116]. Generally, a PHS plant in the "Natura 2000" areas, that fall under EU legislation, might only be authorized if the applicant can demonstrate (by expert opinions) that there will not be any severe negative impacts on the "Natura 2000" protected areas, a burden which probably will be rather high.

Unlike for the German EEZ, construction in the German territorial sea is subject to the adjacent German federal state as the competent authority to grant the construction and operating permits. As for projects in the EEZ, the permitting process necessitates the involvement of all stakeholders and the consultation of all other authorities being the competent authorities for issues which might potentially be affected by the project. The relevant law is the Federal Water Resources Act (WHG) [117]. According to this Act the construction of a plant such as a PHS plant will be considered as modification of a waterbody. The applicant has to provide the authority with an environmental impact assessment according to UVPG. It should be noted that the use of the seawater and its "recycling" back into the sea are as well subject to permits according to the WHG. Within the territorial seas, special attention must be paid to the fact that according to the BNatSchG there are 3 national parks in the German coastal zone. The applicable laws regarding these national parks stipulate to which extent the "use" of these national parks will be allowed. Generally, the laws restrict or even ban any use which might endanger the purpose of the protection as national parks.

Though this section mainly deals with the specific case of German administrative law as relates to permitting of a PHS facility in the German EEZ or territorial waters, similar procedures exist throughout the EU. Such procedures will need to be followed in order for projects to be permitted.

However, national laws might be modified in the course of the energy transition process taking into account new technologies with wider acceptance as environmentally friendly and economic methods to achieve long-term climate targets.

6.2. Environmental aspects

Coastal marine areas are characterized by the highest values of ecosystem services and by multiple uses that are often in conflict with one another [118]. Hydropower applications pose a series of environmental impacts: some do not differ much from those caused by coastal infrastructural works (e.g. ports, coastal works), others are technology-specific but mostly result in fish mortality, either directly or indirectly [119].

Ecologically-sensitive areas require careful planning and thorough assessments of the ecosystem impacts. Hydrodynamics and seabed morphology are the two most affected compartments along all construction phases in turn affecting biodiversity and ecosystem functioning [50, 120]. In particular, (i) changes in salinity and oxygen stratification reflecting on organic matter decomposition rates, (ii) increased turbidity of coastal water affecting photosynthetic efficiency of primary producers, (iii) disrupted transport of fish larval stages posing threats to nursery areas and (iv) an overall impoverishment of the habitat structural complexity threatening pelagic, benthic and avian species were reported.

Mitigation measures, defined as "measures that would avoid, reduce and, if possible, offset significant adverse effects", are outlined in the Environmental Impact Assessment report produced at the end of the EIA process. Impacts can be minimized by scaling down or relocating the project site as well as by applying additional measures to reduce the impacts either at the source or at the receptor [121].

Offset measures compensate for negative biodiversity impacts by providing measurable conservation gains that persist at least as long as projected impacts [122]. Offsets may consist in management interventions such as restoration of degraded habitats or spatial extension of already protected sites such as Special Areas of Conservation (SACs), Special Protection Areas (SPAs) and Site of Community Importance (SCIs) to counteract the loss of biodiversity, habitats or species. Specifically, restoration measures can be classified as active, when habitat-forming species are transplanted/restocked (e.g. Piazzi, 1998 [123]), or passive, achieved with the use of both artificial (e.g. artificial reefs) [124] and natural (e.g. honeycomb worm *Sabellaria alveolata*) hard substrates [125].

Enhancement measures improve the overall biodiversity levels over time in that so-called umbrella species provide adequate structural complexity for the ecosystem. Their selection must be based on precise criteria [126]. The European flat oyster (*Ostrea edulis*) is an optimal candidate because their biogenic structures facilitate the resettlement of several associated benthic species and can attenuate waves and retain sediments [53].

The European legal requirements impose a good ecological status (GES) of marine waters that is to be achieved by protecting biological communities [127]. The status of fish populations, which are considered by multiple descriptors among the 11 of the Marine Strategy Framework Directive, is first investigated in conditions of minimal anthropogenic impact pre-installation (baseline); hydropower-related impacts are then assessed in terms of survival, with particular reference to migration routes and spawning grounds: mathematical modeling predicts turbine encounter and fish injury rates, which are validated by netting/electrofishing seasonal surveys; cameras and sensors assess fish behavior in the vicinity of operating turbines and record the flow conditions; radio tagging and recapture techniques at experimental sites quantify the extent of physical injuries for developing exact mitigation measures; acoustic telemetry reconstructs the 2D behavioral preferences and migration pathways of fish at dams which are then exploited to design optimal passage solutions [128,129].

Hydropower impacts on local and migratory fish may be primarily mitigated by designing environmentally friendly turbines [130, 131], installing fish protection screens and constructing fishways allowing for the bypass of hydroelectric plants or dams. Prompted by various stakeholders (e.g. WWF Switzerland and European Rivers Network coordinating the Salmon Come Back campaign [132]; Association Saumon-Rhin [133]), both academic research and environmental consulting companies assess fish passability efficiency, a subject that has received increasing attention in the last two decades, by characterizing fish population structure and genetics. Should the structure fail to perform as intended, power companies may opt for solutions as drastic as to demolish power stations, as was the case for the EDF Vogelgrün plant in 2017. Hydropower technologies have so far been evaluated as fish-friendly based on the severity of injuries (e.g. scale loss, haemorrhages, skin wounds) and mortality rates caused by the system physical processes [134], even though precise and universally-descriptive statistics cannot be provided due to the many factors, e.g. type of damage, fish species, life stages, hydropower characteristics, that must be kept in consideration. On the other hand, the study of animals' physiological status has been entirely overlooked. Yet, fish, as all vertebrates, do respond to stressful stimuli such as confinement, handling or physical disturbance [135], and stress levels are paramount for animal welfare. Severe and/or sustained stress responses have neuromodulatory and behavioral effects with major life history consequences [136,137]; these reflect on higher biological levels in terms of inhibitory or interruptive effects on growth, reproduction, behavior and disease resistance [138]. The concentration of the cortisol hormone, a widely recognized stress indicator, can be monitored as a proxy of acute stress.

7. Costs and benefits

7.1. Tidal plants

The high capital cost of TPP construction is the main barrier against more wide-spread development and serves as a valuable lesson for potential low-head SPHS. Capital costs are site specific and vary with the geography and hydrology of a site [139]. The total project costs of La Rance TPP are €801 million today [140] (€3340/kW). However, the dam and the powerhouse construction of the Sihwa TPP generated costs discounted to today of €689 million [141] and €332 million [23] respectively (€4020/kW). Compared to the global weighted-average total installed costs of hydropower projects, €1263/kW in 2018 according to IRENA [142], capital costs of TPPs are considered to be high.

Tidal barrage power plants such as La Rance and Sihwa have been found to have a levelized cost of energy (LCOE) on the same order as the €70/MWh that represents the global average for hydropower plants in general [143–145].

Various equations to predict the cost of energy and the cost-effectiveness of sites are available. Baker [146] approximates the tidal unit cost of electricity (p/kWh) empirically. This author uses physical dimensions like the length of the barrage, the area of the basin and the mean tidal range [22]. Another method for estimating the cost of energy generated by a TPP is by adding the capital recovery cost, which takes into account the amortization period, and operation and maintenance costs per unit of energy [139]. The Gibrat ratio [147] can be used to estimate the cost-effectiveness of a TPP site. It compares the length of the barrage in meters to the annual energy production in kWh. Therefore, the most profitable site has the smallest Gibrat ratio.

7.2. Pumped hydro storage plants

PHS's prime purpose is balancing energy supply and demand on a daily basis (arbitrage) and is secondary purpose is to offer black start and renewable integration capacity. It is expected that by 2040, hydrogen will be the preferred technology for weekly and seasonal storage, PHS for daily storage, and Li-ion batteries for grid balancing from timescales of minutes to hours [148]. Since low-head PHS relies on similar technology as traditional high-head PHS it would be most competitive when equipped with a storage capacity stretching from 10 to 30 h. This is the same range as in the literature [67,149]. Besides daily balancing, a secondary revenue stream can consist of black start support and ancillary services [150].

The dam construction, the pump–turbines and the powerhouse and conveyance system each account for approximately $\frac{1}{3}$ of the total costs [50,67,120,149]. The costs of the dam are highly dependent on the required bank revetment, which can form half of the total dam costs in rough sea conditions [50]. For the pump–turbines it is beneficial to use the largest installable runner possible in order to minimize the number of pump–turbines and their corresponding electrical infrastructure [151,152]. A factor that can limit the runner diameter is the constructability of the conveyance system. Cavitation prevention and the use of draft tubes for a vertical axis pump–turbines can lead to larger construction depths and greater initial expense.

The costs of a circular reservoir with a theoretical vertical dam scale with the storage capacity to the power 0.5 (dam costs rise linearly with the diameter, and the surface area quadratic). For a dam that is not vertical but has an inner slope (e.g. 1:5) the scaling benefit increases, since a larger reservoir 'loses' relatively less storage volume due to the dam structure. This leads to a scaling power of the storage capacity costs of approximately 0.4 [50].

For the power capacity, repeated construction of powerhouse units and conveyance systems to house multiple turbines will result in a scale advantage [152], due to the learning curve during construction, economies of scale and the sharing of equipment and mobility costs.

Maintenance and operational costs for standard PHS vary from 1% to 2.2% of the CAPEX per year [153,154]. To date, the additional expenses to protect and maintain a PHS facility against the saline environment are unspecified, though it is estimated that the la Rance tidal plant incurs annual operation and maintenance (O&M) costs of 1.5% to 2% of its capital cost (EDF, personal communication, 2021). Experiences from the Okinawa Yanbaru seawater PHS station and the La Rance tidal barrage do show that it is possible to operate successfully in corrosive salt water conditions [155], (EDF, personal communication, 2021).

For comparing energy storage technologies and their competitiveness, the levelized cost of storage (LCOS) is generally used. The LCOS includes i.e. the investment costs, annual operational costs, interest rate, lifetime and the yearly 'produced' amount of electricity. New PHS plans are estimated to have an LCOS ranging from €50/MWh to €80/MWh, while Lithium-ion battery prices are expected to fall to €100/MWh by 2040 [156]. Note that even with the LCOS it is difficult to make a fair comparison between large scale and small scale technologies, hence Lithium-ion batteries are still expected to be the preferred technology for short-term and small-scale storage services [148].

For low-head seawater PHS the LCOS is expected to vary between €40/MWh and €140/MWh for a best case and worst case scenario respectively. From this range €100/MWh forms the basic scenario.[2] The large range in LCOS is mainly caused by uncertainty regarding the operational and maintenance costs, the amount of turbining hours per day and the location of the storage system and the corresponding deferral of investments in transmission capacity that can be taken into account. Costs for transmission infrastructure are not included, but will benefit technologies that can be applied locally next to the energy source, like a SPHS scheme next to an offshore wind farm. For a storage basin with 2.65 GW of installed power in the middle of the North Sea the grid deferral can save up to €30/MWh when discounted to the LCOS [51]. This potential saving also applies to any other storage technique that can be applied locally, but not to e.g. PHS, for which the energy first has to be transmitted to a basin in a mountainous region. The LCOS analysis indicates that low-head seawater PHS can be a competitive technology to integrate large shares of renewable energy into the grid.

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[2] For the LCOS basic scenario the capital and operational costs from De Vilder (2017) were used for an offshore facility with 25 GWh of storage capacity and 2.65 GW of turbine power in 20 m deep water and protected against 8 m high waves all around. The capital costs are estimated at €4.65 billion with €110 million per year of operational and maintenance costs. Furthermore 6 turbining hours per day are assumed, 70% roundtrip efficiency, 2% downtime, 5% interest rate and a 100 year lifetime with two complete refurbishments of all the electrical and mechanical parts.

8. Discussion

Most of the experience in seawater energy generation techniques originates from TPP. The only executed SPHS technology remains the Okinawa plant, yet several other projects are expected to be realized in the near future such as the Espejo de tarapacá SPHS. Respecting low-head PHS, no plan has been realized yet. The novelty of the low-head PHS technology opens several research fields tackled in this review paper such as new reversible pump–turbine technology, maintenance of electrical and mechanical components in seawater, methods for identifying adequate locations, ecological and morphological effects as well as the construction of innovative structures and dealing with legislation of multiple countries and localities, thus presenting multiple research opportunities.

Equipment placed in a marine environment suffers more corrosion compared to freshwater. Additionally, equipment in seawater accumulates microorganisms (fouling) that can deteriorate the equipment and reduce efficiency. Several techniques have been discussed that have been put into practice in existing TPPs and in the Okinaka SPHS plant. Effective corrosion prevention measures are cathodic protection, the use of corrosion-resisting materials (stainless steel, FRP, GRP) and the use of coating paint. Antifouling measures include the use of natural biocides in coatings as well as non-stick fouling release coatings. Most TPPs were constructed in the second half of the 20th century, thus including antifouling and anti-corrosion techniques from that time. This review shows that nowadays there is potential for research into new environmentally friendly antifouling and anti-corrosion measures.

As an example of legal constraints to SPHS, a review of the German law regarding construction in the coastal zone was conducted. In case that a suitable location for low-head SPHS is found in a Natura 2000 area, the construction of such a facility will only be approved if it is shown that the project brings more ecological gain in the long term than the damage it causes to the protected area. The novelty of low-head SPHS technologies creates uncertainty in how the marine environment will react to such a project. Due to such legal and environmental constraints, the iLand project already encountered some delays in project execution due to the multiple jurisdictions it was subject to. This paper recognizes legal and environmental issues as critical showstoppers together with investment costs.

Floating solar, which has been shown to produce a mutual benefit with hydropower reservoirs by reducing evaporation while also cooling and enhancing the efficiency of the solar operation, could provide the same mutual benefit with PHS

9. Conclusion

For low-head PHS, a high reservoir is recommended in shallow water (5 to 10 m) and in deeper water (10 to 30 m) a valmeer alternative is more beneficial when looking at the volume balance between dredging and dam construction. However, a high reservoir in shallow (coastal) water can require a higher safety level, due to an increased flood risk to surrounding areas. Even though a higher safety level would imply higher expenses, it is not expected that it would be more costly than a valmeer alternative with a largely unequal dredged volume balance.

Failure mechanisms such as soil uplift, piping and macro-instability due to rapid drawdown have been identified from literature as the most relevant regarding the dam structure for low-head PHS. When adequately designed, these failure mechanisms are not technical showstoppers.

TPPs are currently a competitive energy generating alternative, demonstrating that seawater hydroelectricity can be economically feasible. Similarly to conventional PHS, low-head SPHS would be most competitive when the timescale of storage is between 10 and 30 h. Maintenance costs in seawater are higher than in freshwater but experiences from TPPs and the Okinawa Yanbaru SPHS plant show that operation in this environment is feasible. Finally, this paper shows that low-head SPHS LCOS (levelized costs of storage) vary between €40/MWh and €140/MWh. Thus it is shown that low-head SPHS can be a competitive technology for integrating variable renewable energies into the grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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