



Compressed air seesaw energy storage: A solution for long-term electricity storage

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ABSTRACT

The globe is witnessing a significant energy transformation with an increasing proportion of variable energy sources like wind and solar on the grid. Energy storage solutions are required to enable a seamless integration of these renewable energy sources. This paper presents a novel isothermal compressed air energy storage (CAES) consisting of two floating storage vessels in the deep ocean that operates by balancing the pressure of the upper and lower tanks with the oceanic pressure. The methodology consists of estimating the proposed system's energy storage potential and operational parametrization. Results show that the maximum compression ratio between the two storage vessels is four, which significantly increases the system's efficiency and lowers compression costs. Compressed air seesaw energy storage is a cheap alternative for storing compressed air because it does not require large, pressurized tanks or sand covers. It is expected to cost between 10 and 50 USD/kWh for electric energy storage and between 800 and 1500 USD/kWh for the installed power capacity. Seesaw is an interesting alternative to pumped hydro and hydrogen for long-term energy storage cycles in islands and coastal regions close to the deep sea.

1. Introduction

Variable renewable energy (VRE) sources like solar and wind power have become increasingly affordable, opening the door for widespread adoption. To meet climatic targets like “net zero”, a variety of energy storage options, such as short- and long-term energy storage, must be implemented. Batteries and pumped hydropower storage (PHS) are typically the two electrical energy storage (EES) choices for storing electricity on a grid scale.

Batteries are advantageous because their capital cost is constantly falling [1]. They are likely to be a cost-effective option for storing energy for hourly and daily energy fluctuations to supply power and ancillary services [2–5]. However, because of the high cost of energy storage (USD/kWh) and occasionally high self-discharge rates, using batteries to store energy in weekly, monthly or seasonal cycles may never be

financially feasible [6]. Additionally, the widespread use of batteries in power systems and mobility applications raises concerns about the sustainability of the usage of materials for batteries [7,8]. Gravity energy storage, such as mountain gravity energy storage [9] or PHS can provide long-term, weekly, monthly and seasonal energy storage in mountainous areas [10]. However, there is no viable option for storing a significant amount of electrical energy in areas without mountains, except for converting electricity to other fuels (such as hydrogen or synthetic fuels) with low efficiency and high capital cost. Table 1 presents the specifications of mature energy storage systems [10,11]. This research makes the case that coastal regions near the deep sea can fill this gap with compressed air seesaw energy storage (hereafter called “Seesaw”).

There are now a few operational facilities for compressed air energy storage¹ (CAES). Although the technology's turbomachinery component is based on widely used, mature technologies, CAES has not attracted

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¹ This technology works based on the concept of compressing air when electricity is cheap (charging), storing high-pressure air in a cavern or tank, and expanding air through a turbine to generate electricity (discharge).

Nomenclature

BEST	Buoyancy energy storage technology
CAES	Compressed air energy storage
EES	Electrical energy storage
GEBCO	General bathymetric chart of the oceans
HDPE	High-density polyethylene
OTEC	Oceanic thermal energy conversion
PHS	Pumped hydropower storage
UWCAES	Underwater compressed air energy storage
VRE	Variable renewable energy

much attention. Generally, the cost of CAES is lower than BES and higher than PHS for large-scale storage [12,13]. The biggest disadvantage is the air pressure loss that occurs when it is expanded through the turbine to produce power, necessitating the burning of additional fuel, often natural gas, to raise the air’s temperature and pressure [14]. Adiabatic CAES based on thermal energy storage [15] exists to address these problems. The necessity for geological caverns for air storage, air leakage [16], or the high cost of steel tanks if employed for air storage [17] are a few additional difficulties with CAES. Seesaw resolves these difficulties by applying isothermal compression/decompression and the varying deep ocean pressure to remove the need for salt caverns or expensive pressure vessels.

Seymour suggested in 1997 the first simple rigid Underwater Compressed Gas Energy Storage (UWCAES) solution, which consisted of a long pipe or a small tank with ballast bins [18–20]. The main disadvantage of this system is that only one of the tanks is pressurized, while the other one is the atmosphere. This results in large pressure different ratio between the high and low pressure reservoirs, and thus reduces the efficiency of the system, increasing thermal energy losses. A review of marine renewable energy storage solutions is described in [21]. A review of Underwater Compressed Air Energy Storage is presented in [18,22]. There have been few attempts to construct commercial-scale underwater compressed air storage devices. It consists of a permanent storage location in the water, such as a lake or the ocean, and a compressor on land, above or underwater that pumps pressured air to the storage vessels [23]. Underwater CAES has been the subject of numerous research studies [24–27], and a current project implemented by Hydrostor has been put into practice in Toronto, Canada [28,29]. The most recent proposal for underwater is the Ocean Battery created by Ocean Grazer, which applied isothermal CAES underwater. However, they still require expensive pressure tanks to store the compressed air.

This issue is solved in Seesaw.

Recently, isothermal air compression concepts have been explored in the literature and industry. A cylindrical piston expander improved by spraying water into the cylinder was proposed by Zhang et al. (2018) [30–32]. An isothermal CAES system based on a hydraulic pump/turbine and spray cooling was proposed by Chen et al. (2020) and has a round-trip efficiency of 76 % [33,34]. In conjunction with wind energy, Bennett et al. (2021) suggest storing isothermal compressed air energy in saline aquifers [35]. Patil and Ro et al., from North Carolina State University and Baylor University, continue their research on UWCAES while focusing on isothermal compression methods [36–39]. Similarly, a team from the University of Nantes and SEGULA Technologies is working on a UWCAES focused on isothermal compression/expansion [40,41]. There is little doubt that isothermal compression and expansion may considerably enhance round-trip energy efficiency. Most research for improving heat transmission and attaining isothermal processes is based on the liquid piston idea, which is accompanied by liquid spray, wire mesh, porous media and water-gas two-phase foam [18]. Based on quasi-steady-state theoretical analyses and low-speed trials, a very high exergy compression efficiency in the 85–95 % range was attained [42,43]. However, when considering the transient operation of the system and the off-design operation of hydraulic facilities, the performance degenerates. There is currently a scarcity of research that take into account actual different operational circumstances [18]. With an 81 % round trip efficiency, the AirBattery is an industrial isothermal CAES device that stores air by isothermally displacing it with water [44–47]. Water entering the isothermal compressor tank is pressurized by a pump. The air is pumped into one of the compressed air storage tanks when the tanks fill with water and its pressure rises. After that, electricity is produced by forcing water into a hydropower turbine using compressed air. The technique, however, has a major issue that this paper aims to fix as it relies on expensive pressure tanks (CAPEX estimated at 250 USD/kWh).

This article contributes to the ongoing developments in offshore energy storage. The main contributions are: (i) novel technology that integrates isothermal compression and underwater CAES with two floating vessels, with low pressure ratio between the two vessels and without the need for large pressurized tanks or sand cavers (ii) description of the operation of the technology and isothermal compression/decompression, and (iii) first cost estimation and global potential for the technology. This paper demonstrates that Seesaw is particularly interesting for long-term energy storage cycles such as weekly, monthly and seasonal. The proposed design was originated by the writers; it is not a technology found in literature or industry.

Table 1
Specifications of mature energy storage systems [10,11].

ESS	Power rating (MW)	Energy density (Wh/kg)	Power density (W/kg)	Storage duration	Self-discharge per day (%)	Discharge time	Response time	Lifetime (years)	Impact on environment
PHS	100–5000	0.5–1.5	–	hrs -years	Very small	1–24 h+	1–2 min	40–60	Substantial, massive zones of natural landscapes are needed.
CAES	5–300	30–60	–	hrs-months	Small	1–24 h+	1–2 min	20–40	Emissions from the burn of hydrocarbons.
H ₂	0–50	80–10,000	500 +	hrs-months	0	Secs-24 h+	Secs-mins	5–15	Insignificant because a by-product is water.
Lead Acid	0–20	30–50	75–300	mins-days	0.1–0.3	Secs-hrs	Secs	5–15	Lead is toxic and polluting for soil and water.
NiCd	0–40	50–75	150–300	mins-days	0.2–0.6	Secs-hrs	Secs	10–20	Cadmium is poisonous and hazardous for health and the environment.
Sodium-Sulfur	0.05–8	150–240	150–230	secs-hrs	20	Secs-hrs	Secs	10–15	Substantial because the liquid sodium can react with water in the environment.
Lithium	0–0.01	75–200	150–315	mins-hrs	0.1–0.3	Mins-hrs	Secs	5–15	Relatively low, generally affects via emissions in cell production.

2. Methodology

Fig. 1 displays the methodological framework used in the paper. It is divided into three main steps. The Seesaw concept is described in Step 1. It provides a thorough explanation of the Seesaw system as well as the components and isothermal air compression. The technology’s capacity for energy storage is determined in Step 2. The global potential of Seesaw is estimated in Step 3.

2.1. Compressed air seesaw energy storage (Seesaw)

Fig. 2 presents the components of Seesaw. 1) The underwater transmission line is required to connect the grid to the Seesaw plant; 2) The upper storage vessel is made of two high-density polyethylene (HDPE) pipelines, the inner pipeline is filled with compressed air, and the outer pipeline is filled with sand and water. The sand and water are added to increase the weight of the pipeline so that the pipeline’s altitude can have a slight buoyancy at 1000 to 3000 m deep and 103 to 308 bar pressure, respectively. The upper storage vessel is then held in place with an anchor and cable that balances the buoyancy of the upper and lower storage vessels. 3) The lower storage vessel is similar to the upper storage vessel but reaches equilibrium around 2000 to 6000 m deep and 205 to 615 bar pressure, respectively. The selection of air as the compression gas is due to its low costs. Hydrogen would be the ideal gas due to its low density and compressibility. However, it would double the capital costs of the project due to the large volume of hydrogen required to fill the vessels. More details on the selection of the compressed gas are described in [48]. 4) The pipeline is used to transport the compressed air from the upper to the lower storage vessel and vice-versa. It is 1 to 5 km long and should sustain the difference in pressure with the outside pressure. When the pipeline has an angle, the pipeline’s weight is supported by the compressed air inside and the storage vessels. When the pipeline is horizontal, the weight of the pipeline is supported only by the lower storage vessel. A metallic structure inside the lower storage vessel is required to distribute the weight of the pipeline across the lower storage vessel. The pipeline is also used to keep the upper and lower storage vessels together. A similar but smaller metallic structure is required in the upper storage vessel to keep the vessels linked. The pressure of the pipeline close to the upper storage vessel is similar to the surrounding pressure, but close to the lower storage site, the pressure

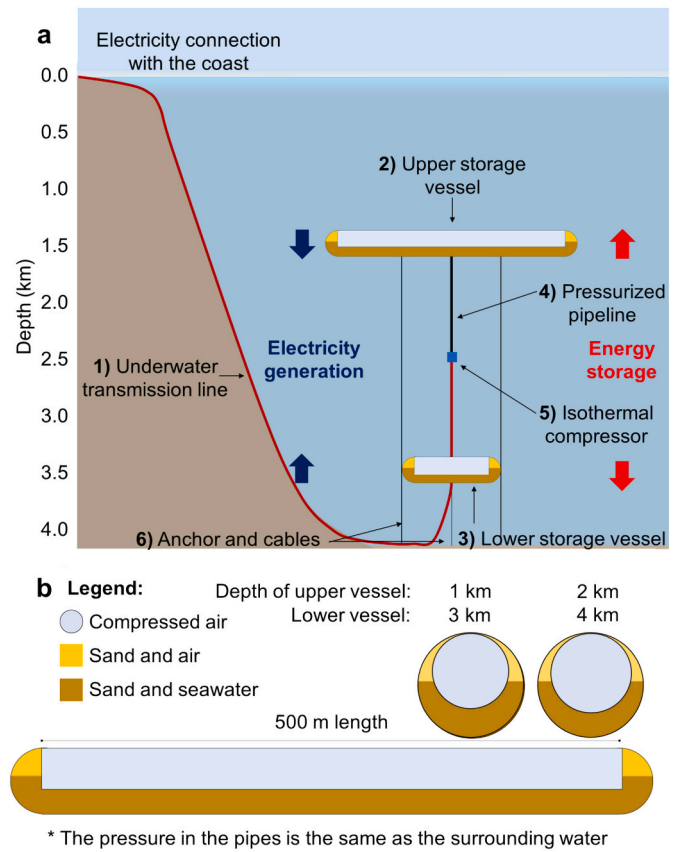


Fig. 2. Compressed air seesaw energy storage, (a) technology overview, (b) storage vessels.

inside the pipeline is significantly smaller. This is because of the lower density of the air. A smaller water pipeline is also required to transport water with dissolved air from one vessel to the other to balance the buoyancy of the two vessels.

The isothermal compression (5) uses water and reversible pump/turbines to displace air in high pressure tanks to compress and

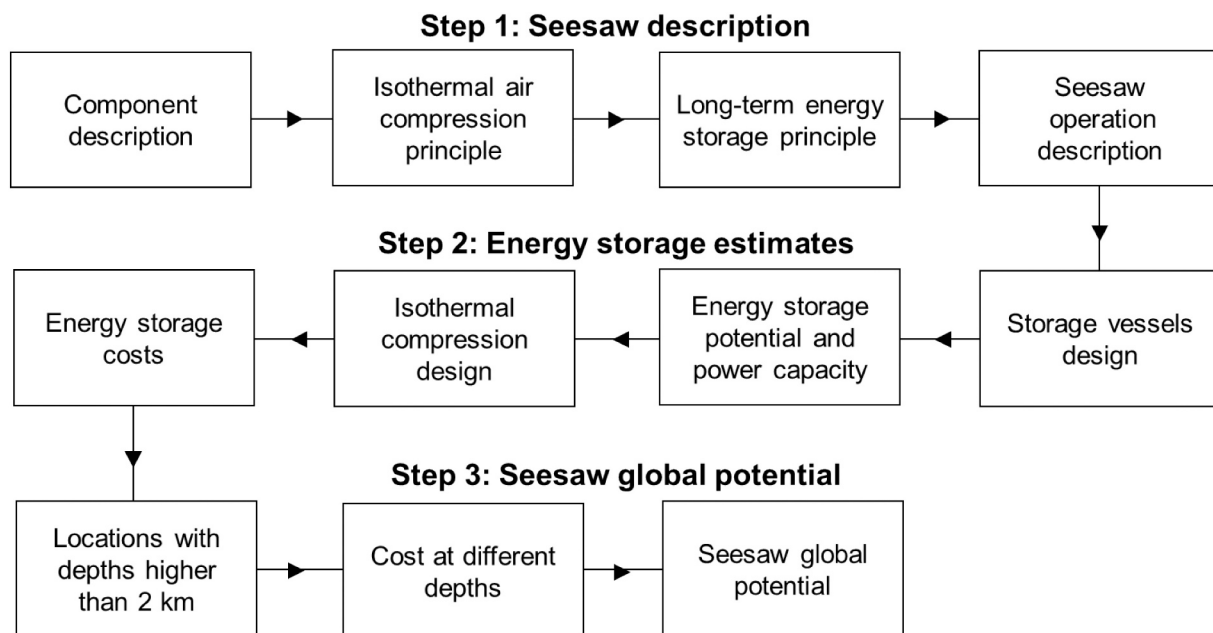


Fig. 1. Compressed air seesaw energy storage (Seesaw) methodological framework.

decompress the air isothermally. Compressed air flows from the upper to the lower storage vessel and vice-versa. The compressed air is used to push water in the isothermal decompressor tank to generate electricity. Alternatively, water is used to push compressed air in the isothermal compressor tank to store energy. This process can have round-trip energy storage efficiencies of 80 %, using a similar system to the AirBattery [44–47]. The system efficiency varies mainly with the pressure difference ratio between the upper and lower reservoirs (future work is suggested to analyze the correlation between the pressure difference ratio and the efficiency of the system), the CAPEX and the quality of the equipment (mainly turbine and generator) applied in the system. The isothermal compressor is located attached to the pipeline between the upper and lower storage sites. This aims to reduce the costs of the isothermal compressor pressure vessels. This is because the surrounding water pressure of the compressor will be the average of the upper and lower storage sites, which allows the isothermal compressor tanks to hold only half of the pressure difference of the Seesaw plant. Sometimes the pressure of the isothermal compressor tank will be higher than the surrounding seawater pressure, other times, it will be lower. For example, if the total pressure difference between the upper and lower storage sites is 100, 200, or 500 bar, the isothermal compressor tanks would only need to hold a 50, 100, or 250 bar pressure difference, respectively. The higher the pressure difference, the higher the benefit of halving the pressure in the isothermal compression tanks. This position of the isothermal compressor also reduces the pressure of the pressurized pipeline, as shown in Table 2. Isothermal CAES was selected for Seesaw because diabatic CAES would significantly reduce the system’s efficiency, and adiabatic CAES would not be practical to be implemented underwater due to the need for thermal energy storage tanks.

The isothermal compressor/decompressor proposed in this paper consists of the process described in Fig. 3. The system consists of two pressurized tanks filled with water. The volume of water is equivalent to half of the volume of the systems tanks, pipes, and turbine. In generation mode, the compressed air enters Tank 1 at high pressure (410 bar) and displaces the water in Tank 1, which passes through a turbine generating electricity and filling Tank 2 at a lower pressure (103 bar), displacing the compressed air in Tank 2 at the same pressure. After Tank 1 reaches a quarter of its volume, the compressed air input to Tank 1 stops and the air is decompressed from 410 to 103 bar. The pressure in Tank 2 remains at 103 bar, and the gas continues to output Tank 2. The reduction in pressure difference results in a reduction in the hydraulic generation head of the turbine. After a certain pressure difference, the hydraulic generation head is so small that the turbine stops generating electricity and the remaining air flows directly to Tank 2. When the pressure in Tank 1 reaches 103 bar, the process starts again, but the tanks switch roles. Two important features of the system are to switch the compressed air inlet from Tank 1 to Tank 2 and vice-versa, which can take a few seconds. To make sure that the system supplies electricity continuously, a battery can store excess electricity generation when the hydrological head is high and generate electricity when the turbine stops generating electricity. During storage mode, the pump displaces the water in Tank 2, so that compressed air at low pressure (103 bar) can enter the tank. Electricity is used to operate the pumps, which increases the pressure of

the water and fills Tank 1. The pressure of Tank 1 increases from 103 to 410 bar as no compressed air exits the tank. After Tank 1 reaches three-quarters of its volume and the pressure reaches 410 bar, compressed air is extracted from Tank 1, until the tank is filled with water. After Tank 1 is filled with water, the process starts again, but the tanks switch roles.

The Anchors and cables (6) support the upper and lower storage vessels, which are designed to have a small floatability so that they can behave similarly to a seesaw during compression and decompression. They are also used to avoid the system being pushed away by oceanic currents. The anchors can also be made of a smaller pipeline filled with sand and seawater. This would facilitate the installation of the system. The installation of a Seesaw plant is relatively simple. It consists of building the vessels, pipeline, isothermal compressor, and anchor in a harbor and transporting the vessels filled with air and equipment to the location where the plant will be installed during good weather not to damage the vessels and equipment. The pipeline with isothermal compressor and the anchors and cables are attached to the vessels. The vessels and anchor are lowered to their discharged operation. While the vessels are lowered, compressed air is injected into the vessels so that the air pressure is the same as the surrounding oceanic pressure. This is performed by lowering tanks filled with compressed air attached to the upper and lower storage vessels. These tanks will perform several trips from the ocean surface to the storage vessels to fill the entire upper and lower storage vessels with compressed air. The anchor is positioned in a stable location at the bottom of the ocean, and the system is ready to operate.

The basic concept that makes Seesaw a competitive energy storage alternative is that the pressure inside the upper and lower storage vessels will always be the same as the pressure of the surroundings. Thus, it is possible to build the storage tank out of low-cost HDPE pipes, resulting in low energy prices and the ability to use the technology to store energy in weekly, monthly, or even seasonal cycles. Similar proposals have been investigated in [49]. The loss of air through the pipeline’s wall is small, particularly with HDPE (PE100). The air penetration potential for HDPE under high-pressure circumstances is negligible [50].

Desert sand is the cheapest and most appropriate material to counterbalance the buoyancy potential of compressed air and has the appropriate porosity to store water to balance the two vessels. To estimate the minimum required amount of sand and water in the storage vessels to maintain it floating slightly, the buoyancy equilibrium can be found in Eqs. (1) and (2) [49].

$$\begin{aligned} & \text{displaced seawater volume} \times \text{seawater density} \\ & = \text{vessel volume} \times \text{vessel density} \end{aligned} \tag{1}$$

$$V \times \rho_{SW} = V_{WS} \times \rho_{WS} + V_{DS} \times \rho_{DS} + V_A \times \rho_A + M \tag{2}$$

V is the tank’s volume, ρ_{SW} is the seawater density (1028 kg/m³), V_{WS} is the wet sand volume, ρ_{WS} is the wet sand density (2000 kg/m³), V_{DS} is the dry sand volume, ρ_{DS} is the dry sand density (1600 kg/m³), V_A is the compressed air volume, ρ_A is the compressed air density (the variation with depths was taken from [51]), M is the pipeline mass (neglected). The dissolved air in seawater is also neglected but should be considered in real projects. The seawater pressure variation with depths is from [52].

Electricity is generated by displacing water in the isothermal decompressors, which then passes through hydroelectric turbines. The energy storage potential of Seesaw is calculated with an estimation of the water that passes through the hydraulic turbine with Eq. (3) [53].

$$E = \int_{i=d}^D (Pl_d - Pu_d - Pp_d) \times c \times V_d \times \rho_w \times g \times e_i \times e_f \tag{3}$$

E is the Seesaw plant energy storage potential in Joules, D is the depth of the upper reservoir in meters, d is the initial depth of the upper reservoir in meters, Pl_d is the pressure of the lower storage vessel at depth d , Pu_d is the pressure of the upper storage vessel, Pp_d is the

Table 2
Pressure along the pressurized pipeline.

Pressure pipeline depth (m)	Upper vessel at 1000 m depth	Upper vessel at 2000 m depth
	Pressure in the pressure pipeline (bar)	
1000	0	
1500	-51	
2000	-102	0
2500	-153	-51
3000	51	0
3500	102	51
4000	153	

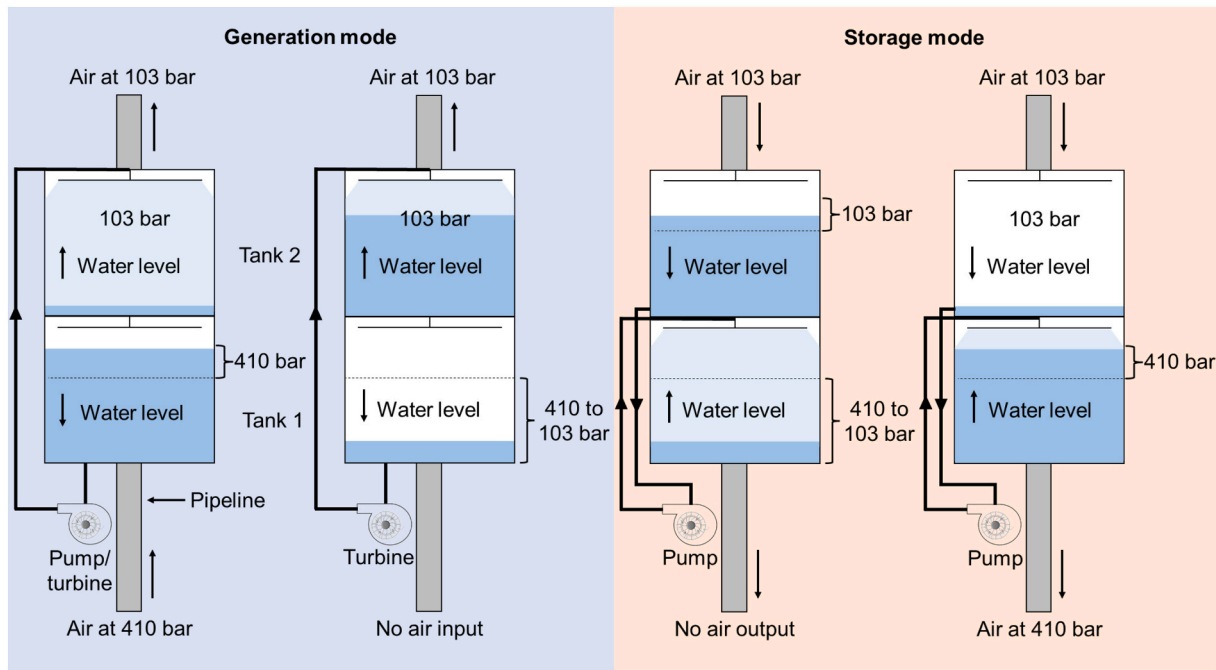


Fig. 3. Proposed isothermal compression/decompression system.

pressure loss in the pipeline as a result of the air density along the pipeline, c converts the pressure different in the vessels from bars into equivalent water hydraulic head and is assumed to be 9.9. This value varies with the density of the seawater. V_d is the volume of air available to displace the water in the isothermal compressor during generation, ρ_w is the water density used in the isothermal compressor (1000 kg/m^3), g is the gravity acceleration (9.81 m/s^2), e_d is the efficiency of the isothermal decompression system. This efficiency depends on the isothermal decompression system, the charging and discharging time, and the heat exchange between the compressed air and the surrounding seawater. This is discussed in the Results section. e_t is the efficiency of the turbine and generator, assumed to be 90 %, e_f is the friction losses due to the movement of the vessels in the deep sea. This value is neglected as the vessel moves very slowly (for example, 2 km in one week).

3. Results

Applying Eq. (2) to a Seesaw project as described in Fig. 4, the air volume in the upper and lower vessels are 50 % and 57 %, respectively. The sand and water volumes are described in Table 3. When the Seesaw plant is discharged, the volume of water in the upper reservoir increases by $83,200 \text{ m}^3$ when reduced from 1000 to 2000 m, and in the lower reservoir reduces by $24,334 \text{ m}^3$. This water cannot be discharged to the surrounding ocean because the dissolved air in the seawater would be lost. To balance out this change in water volume required to reach

Table 3
Design of the upper and lower storage vessels.

	Upper reservoir		Lower reservoir	
Depth (m)	1000	2000	3000	4000
Air pressure (bar)	103	205	308	410
Air volume (%)	50.0	50.0	57.0	57.0
Sand and seawater volume (%)	40.0	19.2	33.3	14.8
Sand and air volume (%)	10.0	30.8	9.7	28.2
Vessel volume (m^3)	1000,000	1000,000	328,843	328,843
Change in water volume (%)	-	83,200	-24,334	-
Air volume (m^3)	540,000	623,200	200,200	224,534

balance at these depths, a water pump can be installed to pump water from the lower to the upper reservoir during generation mode. The pumping head for transporting water is 10 to 30 m (depending on the depth of the systems) and can be neglected. The leftover $58,866 \text{ m}^3$ of seawater that needs to leave the upper vessel can be stored in a bag attached to the upper vessel. The bag would float slightly because the density of the seawater with dissolved air is lower than the surrounding seawater. To estimate the air volume in the vessels, the porosity of the sand is assumed to be 40 % of the sand volume.

Fig. 5 presents the results for the energy estimated from the system. Fig. 5 (a) presents the air density at different depths from 0 to 10,000 m. Fig. 5 (b) shows the head and pressure loss in the vertical, compressed air pipeline that connects the upper and lower vessels. Fig. 5 (c) presents the energy storage potential of several Seesaw project arrangements. More details on these arrangements are presented in Table 4, assuming a seawater density of 1.028 kg/m^3 . As can be seen, the higher the difference in depth between the upper and lower storage vessels, the higher the energy storage potential. Fig. 5 (d) presents the pressure difference between the upper vessel when charged and discharged. This pressure difference is particularly interesting in estimating the costs of the isothermal compression system. For example, in the system where the charged upper storage vessel sits at 0 depth and uncharged at 2000 m deep, the pressure of the tank must increase from 1 bar to 205 bar. This is a pressure 205 times larger. This is not practical for an isothermal compressor that requires vessels to store the pressurized gases. On the other hand, in the Seesaw project, the charged upper storage vessel sits at a depth of 1000 m and uncharged at 2000 m, the pressure of the tank must increase from 103 bar to 205 bar. This is a pressure only 2 times higher, which significantly reduces the volume of the isothermal compressor and significantly reduces the costs of the power capacity of the Seesaw plant. Fig. 5 (e) presents an index representing the ratio between energy storage (Fig. 5 (c)) and pressure difference (Fig. 5 (d)). This shows that the most appropriate Seesaw projects analyzed are the ones where the charged upper storage vessel sits at a 1000 and 2000 m depth.

The operation of Seesaw consists of compressing air to store energy and decompressing it to generate electricity. During generation mode, starting from the fully charged state (Fig. 4), the upper storage vessel has

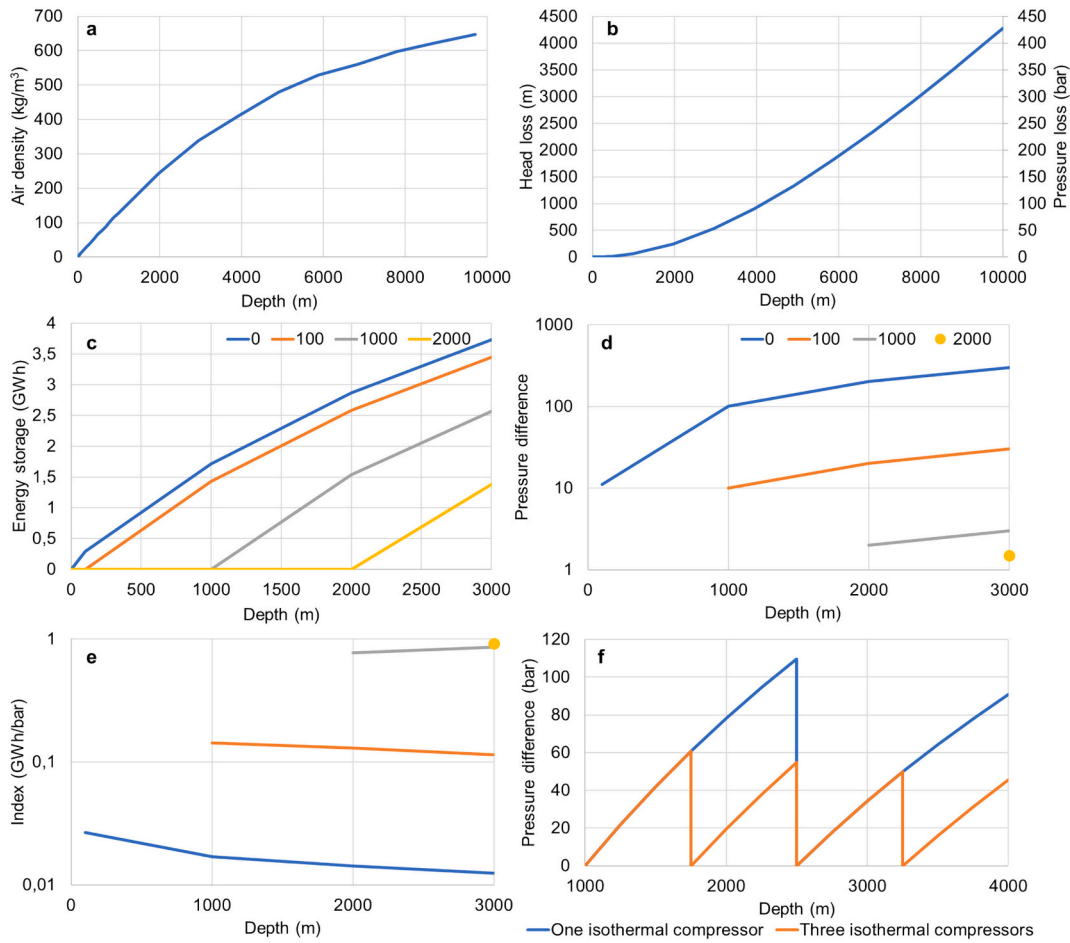


Fig. 5. Characteristics of Seesaw operation. (a) The density of air in the vessels at different depths, (b) head and pressure loss in the vertical, compressed air pipeline, (c) energy storage capacity with different altitudes of the charged upper vessel, (d) pressure difference in the upper vessel discharged and charged, (e) index comparing the energy storage and pressure difference, (f) Seesaw plant with three isothermal compressors in series.

Table 4
Description of the different Seesaw project arrangements investigated in the paper.

	0–100	0–1000	0–2000	0–3000	100–1000	100–2000	100–3000	1000–2000	1000–3000	2000–3000
Upper storage vessel loaded depth (m)	0	0	0	0	100	100	100	1000	1000	2000
Upper storage vessel unloaded depth (m)	100	1000	2000	3000	1100	2100	3100	2000	3000	3000
Lower storage vessel loaded depth (m)	300	3000	6000	9000	3100	6100	9100	4000	7000	5000
Lower storage vessel unloaded depth (m)	200	2000	4000	6000	2100	4100	6100	3000	5000	4000
Head variation loaded (m)	308.4	3084	6168	9252	3084	6168	9252	3084	6168	3084
Head loss in pipeline loaded	5	549	1885	3641	583	1938	3703	864	2372	1124
Head var. loaded with head loss (m)	303	2535	4283	5611	2501	4230	5549	2220	3796	1960
Head variation unloaded (m)	103	1028	2056	3084	1028	2056	3084	1028	2056	1028
Head loss in pipeline unloaded	2	190	674	1337	201	691	1356	294	830	380
Head var. unloaded with head loss (m)	101	838	1382	1747	827	1365	1728	734	1226	648
Hydraulic head variation (%)	67	67	68	69	67	68	69	67	68	67
Energy storage (GWh)	0.29	1.71	2.87	3.73	1.74	2.87	4.30	1.54	2.57	1.38
Pressure difference (bar)	11	101	201	301	10	20	30	2	3	1.5
Index (storage/power)	0.027	0.017	0.014	0.012	0.143	0.129	0.115	0.770	0.857	0.919

a compressed air pressure of 103 bar and the lower 410 bar. The hydraulic generation head of the pump/turbine in the isothermal compressor is equal to 2220 m (3084 m – 864 m, where 3084 is a result of the pressure difference between the upper and lower reservoirs and 864 is the head loss due to the compressed air column in the pipeline). This hydraulic head is very large and would require two or three purposely built multi-stage Francis pump-turbine in series to operate. With the reduction in pressure in the lower vessel, it becomes lighter and

rises. Similarly, as the upper vessel pressure increases, it becomes heavier and sinks. The anchor and cables control the upper vessel’s descent and the lower vessel’s rise. There is a need to pump a small quantity of water from the lower to the upper vessel to maintain the balance between both vessels. While generating electricity, the pressure difference between the upper and lower storage vessels reduces, as well as the hydraulic head in the isothermal decompression. When the pressure of the upper and lower storage vessels reaches 205 bar and 308

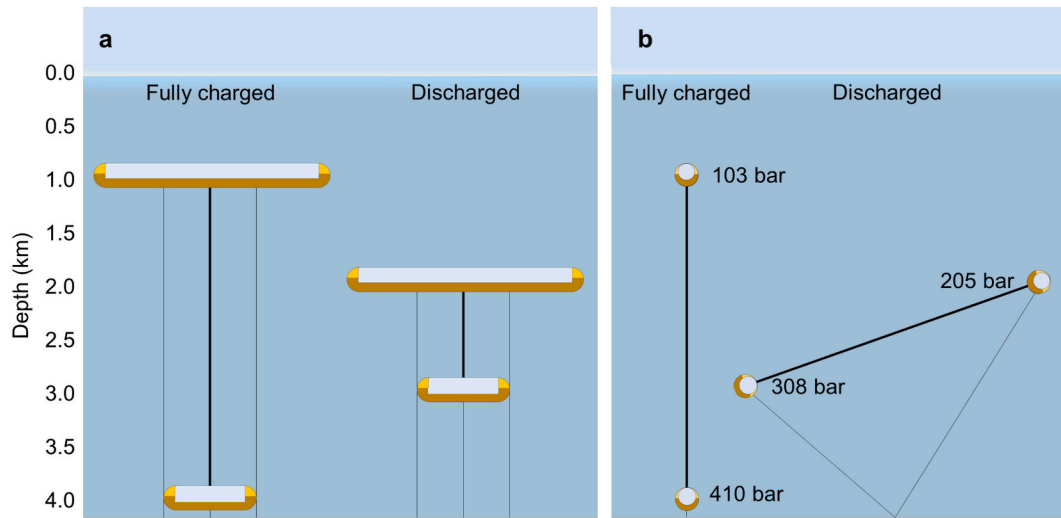


Fig. 4. Compressed air seesaw energy storage fully charged and discharged in (a) frontal view and (b) side view.

bar, the system is fully discharged. The hydraulic generation head of the pump/turbine in the isothermal compressor is equal to 734 m (1028 m – 294 m, where 1028 is the pressure difference between the upper and lower reservoirs and 294 is the head loss due to the compressed air column in the pipeline). This results in a hydraulic head variation of 65.6 % (1–2220/734). The hydraulic head variation should be kept smaller than 70 % to lower the costs for power and increase the round-trip efficiency of the system.

During storage mode, starting from the discharged state (Fig. 4), the upper storage vessel has an air pressure of 205 bar and 308 bar in the lower vessel. With the increase in pressure in the lower vessel, it becomes heavier and sinks. Similarly, the upper vessel pressure reduces, it becomes lighter and rises. While storing energy, the pressure difference between the upper and lower storage vessels and the hydraulic head in

the isothermal compression increase. When the pressure of the upper and lower storage vessels reaches 103 and 410 bar, the system is fully charged.

Assuming the isothermal compression/decompression in Fig. 3 and the need to maintain a constant compressed air flow to maintain the isothermal characteristics of the system, the theoretical power generation profile of the system would look similar to the one presented in Fig. 6 (a), assuming that the hydro turbine that maintains a high generation efficiency with a 100 % head variation, which is not possible. A more realistic electricity generation potential is shown in Fig. 6 (b), whereafter, the head variation is higher than 67 %, and the turbine stops generating electricity. This electricity reduction results in a 7.5 % energy loss. An approach that could be applied to rectify the electricity generated in the turbine and provide constant power is the use of batteries, as

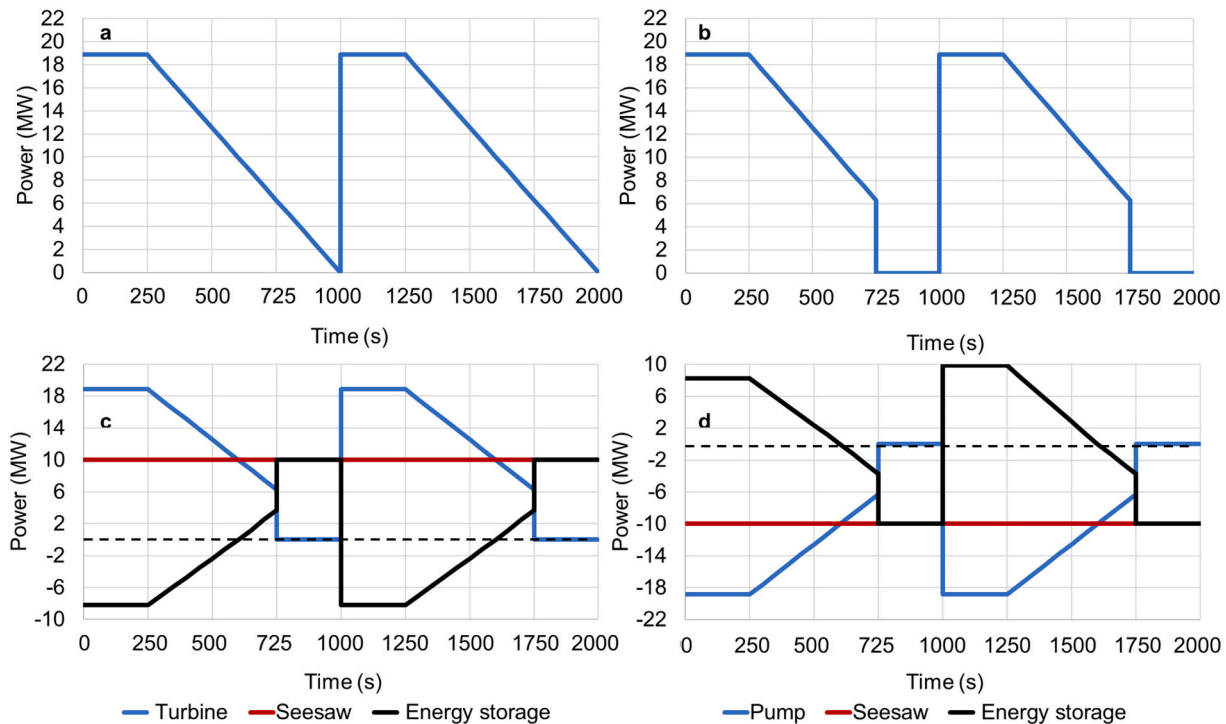


Fig. 6. Characteristics of Seesaw operation. (a) theoretical hydraulic power generation profile, (b) actual hydraulic power generation profile, (c) Seesaw during generation model and (d) storage mode.

shown in Fig. 6 (c). This provides a constant amount of energy, as shown in the red line entitled Seesaw. The higher the charging/dischARGE time, the higher the isothermal compression/decompression efficiency. This is because turbulence in the compressed air increases the temperature of the gas, which increase the energy losses in the system. A high charging/dischARGE time is selected, which increases the CAPEX of the system, and increases the isothermal compression/decompression efficiency. With these operational parameters and assuming a round trip efficiency of the pump and turbine of 90 %, for the battery system 95 % (only applies to 30 % of the power generated), for the isothermal compression and decompression 90 %, the overall efficiency of the system can be estimated at 68 % $((70-7.5) \times 0.9 \times 0.9 + (30-7.5) \times 0.95 \times 0.9 \times 0.9)$. Note that this efficiency can be increased to 80 % $(75 \times 0.9 \times 0.9 + 25 \times 0.95 \times 0.9 \times 0.9)$ if all the generation head is extracted, as in Fig. 6 (a). With a hydraulic head of 2220 m, power generation of 18.9 MW, a generation efficiency of 90 %, the flow of water through the turbine is 0.96 m³/s. As it takes 1000 s to fill up, the water volume in the tanks much be 962 m³.

Another interesting design option to reduce the hydraulic pressure of the turbines and the pressure difference in the isothermal compressors is to install several isothermal compressors along the pressurized pipeline, as shown in Fig. 7. A Seesaw plant with one isothermal compression system would result in a maximum pressure difference of 110 bar in the upper section of the pipeline and 91 bar in the lower section, as shown in Fig. 5 (f). A Seesaw plant with three isothermal compression systems would result in pressure differences of 61, 55, 50, 45 bar.

3.1. Seesaw cost estimation

The cost for Seesaw is not available in the literature, as it has been first proposed in this paper. A cost estimation for Seesaw is presented in Table 5. This is just a preliminary cost estimation, the provided figures might not precisely describe the real cost of the system. It assumes that the charged and discharged upper and lower storage vessel sits at a depth of 1000, 2000, 3000 and 4000 m, respectively. The system under consideration has an installed capacity of 10 MW and a storage capacity of 1.5 GWh. This system can generate electricity for 6.3 days continuously. The project's energy storage cost significantly varies with the plant's installed capacity. With an installed capacity of 10 MW (6.3 days discharge period), the CAPEX energy storage cost is 15 USD/kWh (23,000,000 USD / 1500,000 kWh). If the installed capacity was designed to be 1 MW (63 days discharge period), the energy storage cost

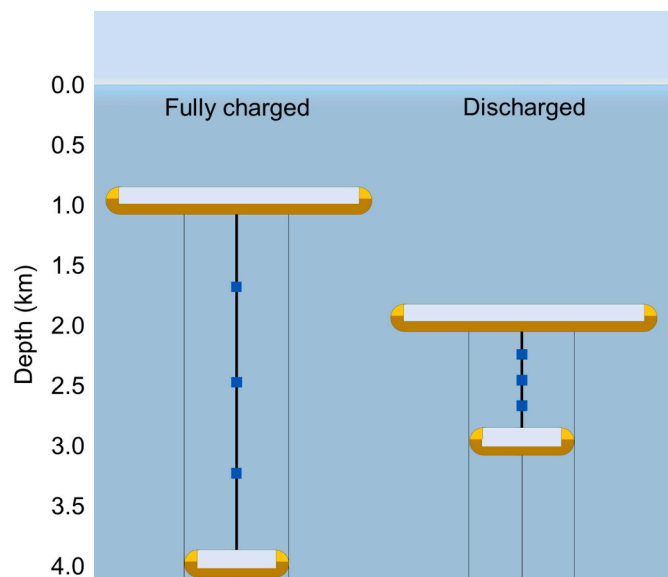


Fig. 7. Seesaw plant with three isothermal compressors in series.

Table 5

Cost estimation for Seesaw components with 10 MW installed capacity and 1.5 GWh storage capacity.

Component	Cost description	Cost
Isothermal compression	Equipment required to perform isothermal compression for 10 MW of energy storage and electricity generation capacity [54].	10 million USD
Vertical, compressed air pipeline	3 km long steel pipeline is required to connect the ship and the deep ocean tanks [55]. The cost of the pipeline is multiplied by 2 so that it resists ocean corrosion.	3 million USD
Storage vessel pipes	4 HDPE pipes. Two with 50 m diameter, one with 500 m (1,000,000 m ³ volume) and the other 164 m (330,000 m ³ volume). One with 36 m diameter, one with 500 m (500,000 m ³ volume), and the other with a diameter of 38 m and 164 m (186,000 m ³ volume). Extrapolating the costs in [56].	3 million USD
Sand	Desert sand for 1 USD per tonne [57]. It is required 1,026,000 t of sand. Density of 1600 kg/m ³ . The sand can be extracted from the deep sea, close to the plant's site location.	1 million USD
Anchor and cables	The anchor and cable cost for Seesaw is not significant. This is because the upper and lower vessels have a small floatability, which can be resolved with pipes smaller than the storage vessel filled with sand and seawater. If the Seesaw plant is implemented in locations with strong oceanic currents, mooring cost can increase significantly.	0.5 million USD
Battery	An energy storage solution is required to guarantee the continuous electricity supply from the isothermal compressor. A battery with 1 MWh is suggested. Assuming a high cost of 500 USD/kWh for a high-power battery with relatively long-life time and the casing to support the high pressure environment.	0.5 million USD
Construction	The construction cost involves offshore services, which are very particular to Seesaw project and not yet available. The following cost estimate assumes that Seesaw is a mature technology. These are: contracting ships and crew required to transport the vessels and equipment to the installation location (2 million USD), the equipment and crew required to connect the vessels with the pipeline, cables, and anchor (1 million USD), the equipment to lower the vessels to its operational depths, including the air-compressor in the ship and compressed air tanks to deliver the compressed air to the storage vessels (2 million USD).	5 million USD
Total project cost	-	23 million USD
Energy storage costs per unit of stored energy	Seesaw with 1.5 GWh energy storage capacity.	15 USD/kWh
Power capacity costs per unit of installed capacity	Installed capacity for storage and electricity generation. This includes the costs of the isothermal compression and the vertically compressed air pipeline.	1.300 USD/kW

is 8 USD/kWh.

Seesaw energy storage costs variation with depth is shown in Fig. 8. To create Fig. 8, different Seesaw operational parameters have been created for different depth (as shown in Table 4). The depth in Fig. 8 corresponds to the depth of the charged lower storage vessel. The equipment costs for the different depths have been accessed, assuming a charge and discharge 6.3 days and power of 10 MW. The volume of the

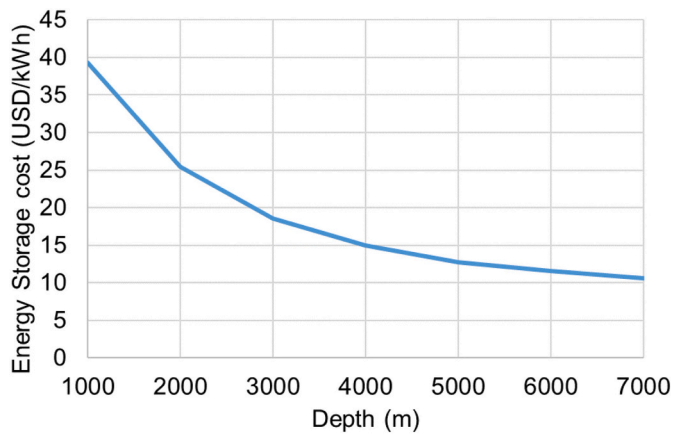


Fig. 8. Seesaw CAPEX energy storage cost (USD/kWh) varying with depth.

upper and lower storage vessels and their costs vary inversely proportional to their energy storage capacity in Table 4. The higher the depth, the smaller the volume of the storage vessels. The system’s construction costs vary according to [48,58], assuming 4000 m as the standard comparison depth, as shown in Table 5. The equation used to estimate the costs is presented in Eq. (4) [48].

$$C_d = \frac{E_d}{T_d} \tag{4}$$

where, C_d is the energy storage cost at depth d , E_d is the energy storage capacity of the Seesaw plant and T_d is the total cost of the plant at a given depth.

3.2. Seesaw global potential

A computational model has been used to evaluate Seesaw potential globally. Bathymetry data from GEBCO [59] was used with a 30 arc-second resolution, or 900 m at latitude zero. The global potential for Seesaw is shown in Fig. 9. Each 30 arc-second resolution pixel with the greatest depth is downscaled to one degree of resolution to better present the results. The depth shown begins at 2000 m to enhance data visualization. The relationship between ocean depth and storage costs is seen in Fig. 8. The biggest potential for Seesaw is in oceanic islands, Indonesia, the Philippines, Australia, Japan, the United States, Mexico,

Chile, Peru, Ecuador, Colombia, Cuba, Brazil, Jamaica, Guatemala, Honduras, Oman, Somalia, South Africa, Ghana, Madagascar and Portugal.

3.3. Seesaw operation

This paper investigates the construction of a floating offshore wind power project with 1 GW of installed capacity close to Tokyo, Japan, with a Seesaw and battery system with an installed capacity of 500 MW and a storage capacity of 50 GWh, which consist of 33 Seesaw plants. Seesaw is used to reduce wind generation fluctuations (represented by the blue line in Fig. 10 (a)). Data from the Renewable Ninja site [60] at 34.6761 latitude and 141.8244 longitude was used to create the hourly offshore wind power profile in 2019. The targeted demand output from the hybrid offshore wind power, Seesaw and battery plant is 500 MW (represented by the black line in Fig. 10 (a)). The energy storage capacity of the Seesaw plant is represented by the blue line in Fig. 10 (b) in GWh. The grey and yellow lines in the same figure represent the maximum and minimum energy storage levels, respectively. As can be seen, the Seesaw plant operates as it is intended to store energy in weekly and monthly cycles and sporadically in hourly and daily cycles. This is handy since energy storage (GWh) is cheap in Seesaw, despite its relatively high installed capacity cost (GW). The red line in Fig. 10 (a) shows that there are losses in the energy storage system since it lacks the storage capacity needed to accommodate all extra offshore wind power. Occasionally the system is insufficient to provide the required demand. The amount of energy lost by curtailment equals 11.5 % of the total electricity produced by offshore wind.

4. Discussion

Seesaw is installed in the deep sea, distant from conventional power demand. As a result, its application is limited to specific situations. The instances where Seesaw might be used are shown in Table 6. Fig. 11 compares the size of a Seesaw plant’s upper and lower storage vessels described in Table 5 with the size of an existing large oil tanker, container, and bulk carrier ships. Table 7 summarizes the advantages and disadvantages of Seesaw.

Seesaw plants are attractive for generating or storing a stable amount of energy in weekly, monthly, or seasonal cycles due to their cheap energy storage cost (MWh) and high-power cost (MW). In contrast, batteries may be employed to offer hourly and daily energy storage. The key features of Seesaw are compared to those of other mechanical and

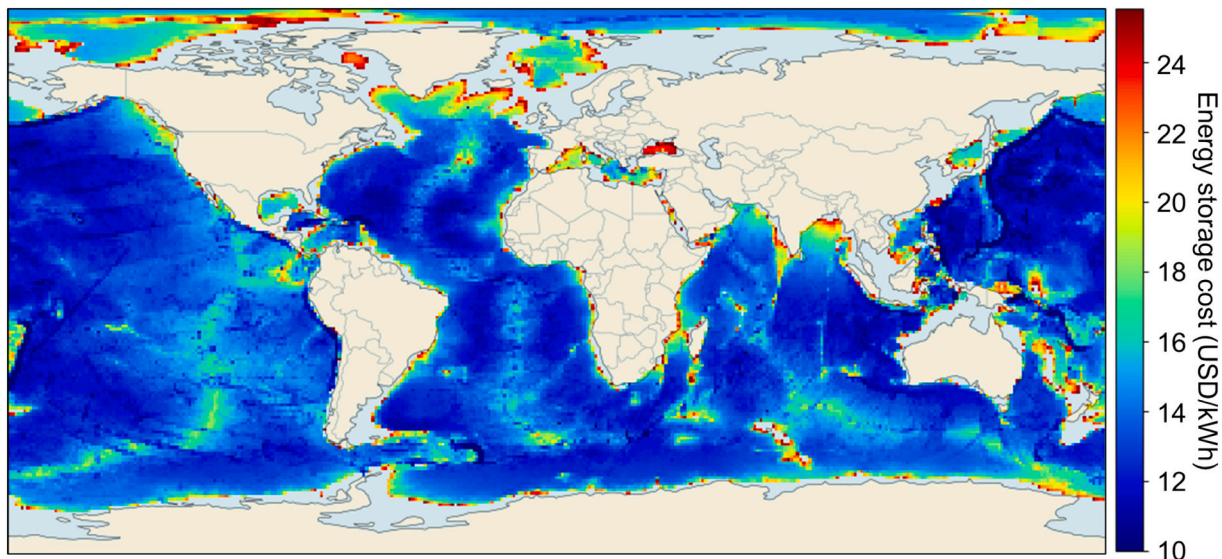


Fig. 9. Global potential for Seesaw.

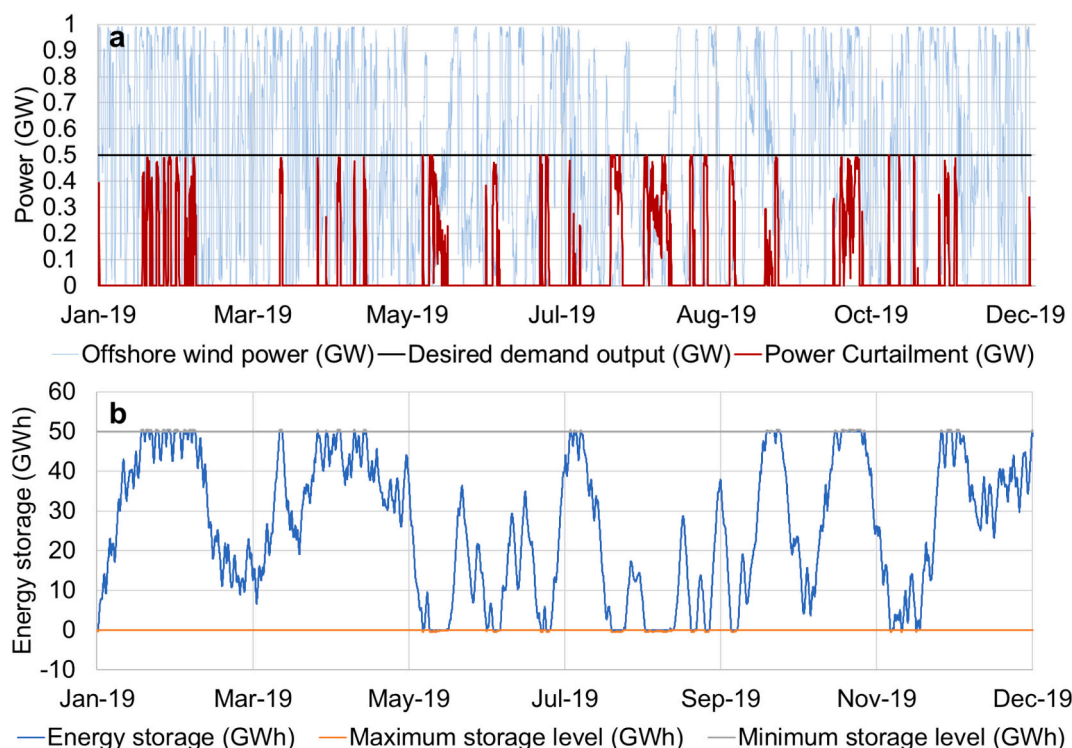


Fig. 10. Seesaw operation to store offshore wind power in front of Tokyo, Japan. (a) wind power, electricity demand and energy losses (GW), (b) energy storage (GWh).

Table 6
Possibly viable scenarios for Seesaw systems.

Scenarios	Description
Long term energy storage	PHS and synthetic fuels, such as green hydrogen and ammonia, are the sole possibilities for monthly and seasonal electricity storage. Hence Seesaw can be used in grids where these alternatives are not practical.
Coastal areas	Coastal locations with little practical pumped-storage potential with weekly, monthly or seasonal energy storage requirements may benefit from Seesaw. Due to the high cost of underwater transmission, it should be noted that project cost rises significantly with the distance between the coast and the Seesaw project.
Islands	Islands are the most interesting case for Seesaw because of the high costs of electricity in islands and the few generation and energy storage alternatives.
Offshore wind power close to the coast	Seesaw is appropriate to store wind energy since it has weekly energy storage cycles. Additionally, because both the Seesaw project and offshore wind power plants might be located in the ocean, reducing the distance between them.
Floating offshore wind power for hydrogen generation	The capacity of Seesaw to store electricity from offshore floating wind farms is substantial. Seesaw plants may be placed beside a floating offshore facility.
Deep sea mining	Deep sea mining initiatives will require a lot of energy in the future. Deep sea mining projects may use energy storage services from Seesaw.

electrochemical energy storage devices in Table 8. Seesaw systems are expected to last for 30 years, with some equipment, including storage vessels, having a longer lifespan and batteries having smaller lifetimes. Keep in mind that investing in technology to minimize component and building costs can drastically lessen the cost. A comparison with different energy storage systems is provided in [61].

Compared to batteries and pumped hydro storage, Seesaw has a significantly smaller environmental impact. Care should be taken to reduce any adverse effects of the system’s operation on seawater vegetation and wildlife. High-quality riverbed sand is currently in low supply worldwide due to the demand for concrete production [64]. On the other hand, desert sand is plentiful and has high porosity and permeability, which Seesaw needs. Resource availability is not an issue for the proposed solution because desert sand is widely available and has substantially fewer consequences than riverbank sand.

In locations close to the tropics, where the difference in temperature between superficial and deep seawater is higher than 20 °C [65], Seesaw can be combined with oceanic thermal energy conversion (OTEC). This could be done by increasing the temperature of the upper vessel from (3 to 25 °C) during compression (energy storage), or by increasing the temperature of the lower vessel during decompression (electricity generation). Heat the upper vessel is more practical due to its proximity to the surface. The integration of Seesaw and OTEC would not result in an overall positive energy balance for the system, but it could increase the overall system’s efficiency.

This study makes the case that Seesaw provides weekly, monthly, and seasonal energy storage cycles, might close the current gap for long term energy storage. For details on Seesaw, batteries, PHS, ammonia, and hydrogen, see Fig. 12. The limitations of batteries and long-term energy storage are highlighted in [66]. Refer to [12] for further information on technologies with short storage cycles. The findings can help energy planners and decision-makers understand the potential costs and advantages of this storage technology compared to other options.

5. Conclusions

Over the past ten years, battery prices have significantly decreased. However, there is still a gap for viable energy storage technologies with weekly, monthly, and seasonal storage cycles in locations with no potential for PHS. Seesaw could provide affordable and long-term energy storage services. Due to its high power costs, Seesaw should be designed

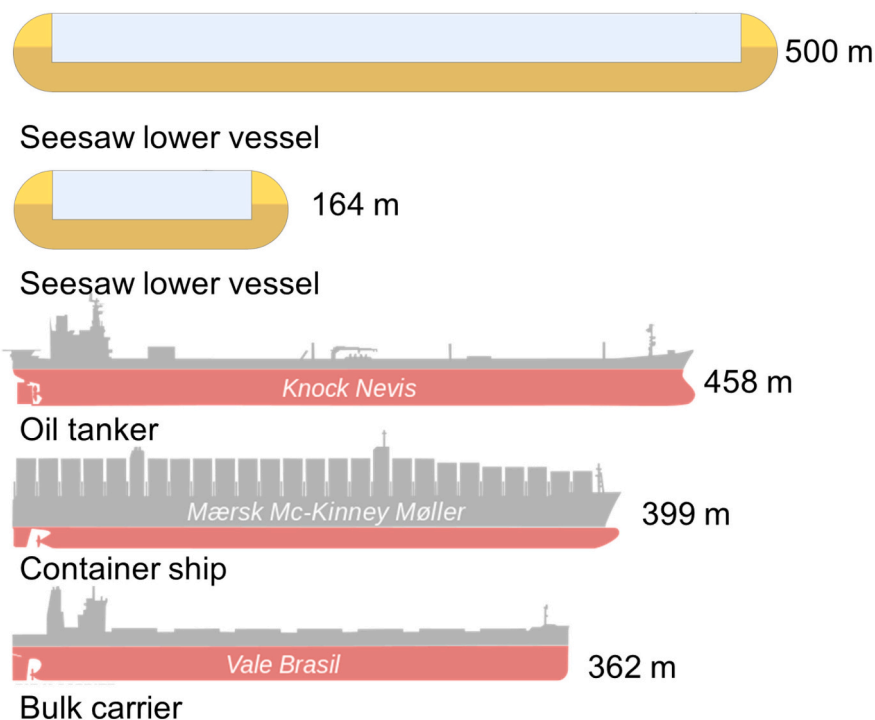


Fig. 11. Size comparison between Seesaw upper and lower storage vessels and some of the longest ships worldwide.

Table 7
Advantages and disadvantages of Seesaw.

Advantages	Disadvantages
The system can be implemented in any location in the deep ocean.	Demand for energy storage that can be resolved with Seesaw is limited to coastal areas and islands, reducing the solution's applicability.
Most material required in the system, apart from the small battery, is abundant, cheap and does not result in CO ₂ emissions. This reduces the environmental impact and geopolitical risks of the technology.	The need for underwater transmission lines increases the cost of energy storage and limits its application to locations close to the deep ocean.
The system has a relatively low power cost because the maximum pressure ratio between the upper and lower storage vessels is only 4. This is significantly smaller than other CAES solutions.	It requires the backup power from batteries, which increases the cost of the system.
A single Seesaw plant can provide hourly, daily, weekly, monthly, and seasonal storage solutions. But preference is given to weekly and monthly storage cycles.	Magnetic bearing is required for the pump/turbines operation at high pressure, which increases costs.
It has no impact on the landscape, as the system is located in the deep sea.	High cost maintenance due to the difficulty of accessing the plant at high oceanic depths, and the highly corrosive environment.
The system is modular. This allows the energy storage capacity of the Seesaw plant to increase with the demand for storage.	In case the plant has to be brought back to the surface for maintenance, the costs of bringing the plant to the surface and returning it to the deep ocean are high.
The system is not fixed to the ocean bed and can be decommissioned from one location and installed in another location if required.	The integration of pump/turbine and battery operation can be challenging.

in combination with batteries. Integrating these technologies would result in a low cost power (USD/MW) and energy storage (USD/kWh) solution. Seesaw generates and stores energy over long periods, while the battery does it over short periods. By using a hybrid system, Seesaw

Table 8
Cost comparison between Seesaw and other technologies [1,48,62,63].

	Installed capacity cost (USD/kW)	Energy storage cost (USD/kWh)	Capacity (MW)
Pumped hydro storage (PHS)	400–1000	2–50	100–10,000
Batteries (Lithium-ion)	250	120	1–500
Buoyancy Energy Storage Technology (BEST)	4000–8000	50–100	10–100
Seesaw	800–1500	10–50	1–100

could operate with high capacity factors by using a hybrid system, increasing its viability. Seesaw projects range in size from 1 to 100 MW, with costs ranging from 800 to 1500 USD/kW for installed capacity and 10 to 50 USD/kWh for energy storage CAPEX. The deeper is the lower storage vessel, the lower the energy storage cost. The biggest potential for Seesaw is in oceanic islands, Indonesia, the Philippines, Australia, Japan, the United States, Mexico, Chile, Peru, Ecuador, Colombia, Cuba, Brazil, Jamaica, Guatemala, Honduras, Oman, Somalia, South Africa, Ghana, Madagascar and Portugal. Although CAES has attracted much scientific interest, there are few industrial applications. In the future, CAES will be a more appealing option for energy storage, especially for long-term energy storage, due to the capability of compressing air isothermally with storage efficiencies greater than 80 %. Also, Seesaw could pave the way for making CAES an affordable long-term energy storage solution in the future.

CRedit authorship contribution statement

Conceptualization, J.H., K.R.; methodology, B.Z; writing—original draft preparation, software, J.H.; writing—review and editing, B.Z; visualization, A.N.; investigation, B.R.; data curation, J.G.; project administration, Y.W.; funding acquisition and resources F.B. All authors have read and agreed to the published version of the manuscript.

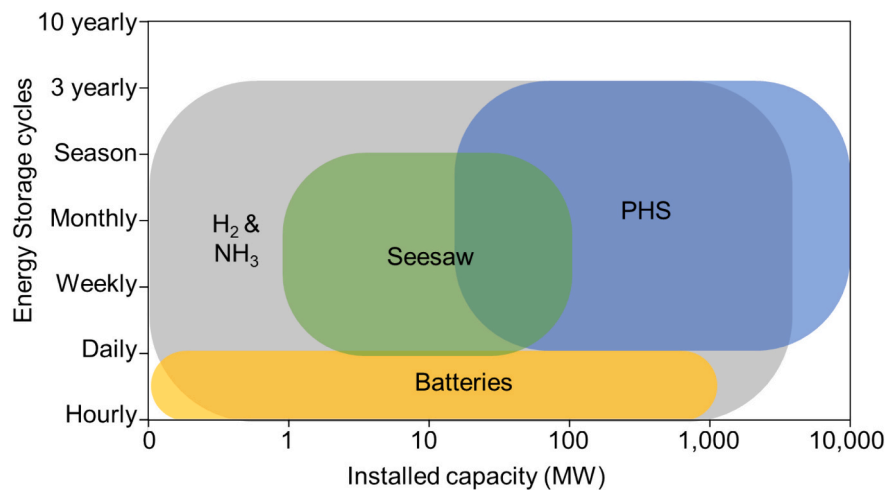


Fig. 12. Comparison of the installed capacities and energy storage cycles of long-term energy storage technologies (Seesaw, PHS, hydrogen, and ammonia) and short-term energy storage (batteries).

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Data availability

Data will be made available on request.

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