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Isothermal Deep Ocean Compressed Air Energy Storage: An Affordable Solution for Seasonal Energy Storage

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Abstract: There is a significant energy transition in progress globally. This is mainly driven by the insertion of variable sources of energy, such as wind and solar power. To guarantee that the supply of energy meets its demand, energy storage technologies will play an important role in integrating these intermittent energy sources. Daily energy storage can be provided by batteries. However, there is still no technology that can provide weekly, monthly and seasonal energy storage services where pumped hydro storage is not a viable solution. Herein, we introduce an innovative energy storage proposal based on isothermal air compression/decompression and storage of the compressed air in the deep sea. Isothermal deep ocean compressed air energy storage (IDO-CAES) is estimated to cost from 1500 to 3000 USD/kW for installed capacity and 1 to 10 USD/kWh for energy storage. IDO-CAES should complement batteries, providing weekly, monthly and seasonal energy storage cycles in future sustainable energy grids, particularly in coastal areas, islands and offshore and floating wind power plants, as well as deep-sea mining activities.

Keywords: energy storage; seasonal energy storage; compressed air energy storage; offshore wind; renewable energies; ocean storage

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1. Introduction

The ever-decreasing cost of variable renewable energy (VRE), such as wind and solar PV, has prepared the path for their widespread adoption [1,2]. However, in order to attain climate objectives such as "net zero", diverse energy storage options, including seasonal energy storage, must be employed [3]. Pumped-hydro storage (PHS) and batteries are the two most used grid-scale energy storage technologies. The capital cost of batteries is rapidly decreasing [4] and might soon provide reasonably priced daily energy storage services [5–7]. However, batteries are not designed to store energy in seasonal cycles given the high energy storage cost (USD/kWh) [8] and self-discharge (lithium-ion batteries have low self-discharge, i.e., 1.5–5%/month, and some batteries have less than 0.5% after 400 days [9]). Furthermore, the high demand for batteries in electric vehicles and grids raises questions about sustainability and resource availability [10,11]. Mountainous regions can provide seasonal energy storage with mountain gravity energy storage [12] and PHS

[13,14]. In locations without mountains or water, converting electricity to synthetic fuels such as hydrogen is seen as the main solution to seasonal energy storage [4]; however, this method has low efficiency and a high capital cost [15]. This paper argues that isothermal deep ocean compressed air energy storage (IDO-CAES) in areas close to the deep ocean can fill this void.

Compressed air energy storage (CAES) is a utility-scale electricity storage solution with a few operational plants today [16]. While the turbomachinery part of the technology is based on commercial, mature technologies, CAES has not received attention due to a few challenges. The main drawback includes the loss of pressure in the air when it is being expanded through the turbine to generate electricity, which creates the need for additional fuel, usually natural gas, to increase the temperature and pressure of the air [17]. Hence, the technology has a relatively low overall efficiency and is not emission-free if natural gas is used for supporting expansion. There are a number of CAES setups that can address these difficulties, including adiabatic CAES, which uses thermal energy storage [18]. Other issues with CAES include the necessity of geological salt caves for air storage, air leakage [19] and the cost of pressure tanks if employed for air storage [20].

Salt caverns can be constructed in locations where the geology consists of salt layers. This is the cheapest alternative to storing compressed air in CAES systems [21]. Even though the potential for salt caverns is significant in some countries, such as Germany [22], locations with salt layers are limited (Figure 1). For this reason, we considered the possibility of expanding the potential for CAES by proposing the construction of cheap compressed air storage tanks in the deep sea.

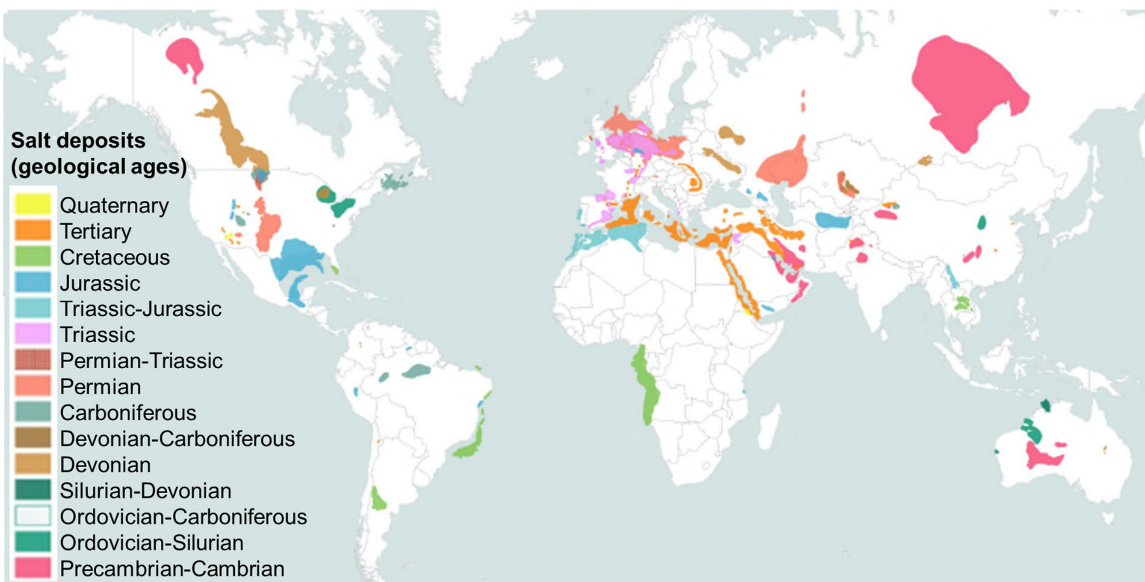

Figure 1. Map of existing salt layers around the world. Adapted from [23].

Seymour proposed the first basic rigid Underwater Compressed Gas Energy Storage (UWCAES) system in 1997 [24–26], which consisted of a small tank or a long pipe with ballast boxes in the deep sea. The primary differences between UWCAES and IDO-CAES is that IDO-CAES uses isothermal compression, which increases energy storage efficiency, and instead of using ballast bins, the pipelines are filled with sand, which is cheaper. In [27], an overview is provided of marine renewable energy storage systems, and in [24,28], a review on Underwater Compressed Air Energy Storage is outlined. A few commercial-scale underwater compressed air storage devices have been attempted. These consist of a permanent storage location in the water, such as a lake or the ocean, and a compressor located either on land or above or beneath the water that pumps pressured air to the storage containers [29]. Several research studies on underwater CAES have been conducted [30–33], and a current project executed by Hydrostor has been put into operation in Toronto, Canada [34,35]. Ocean Grazer's Ocean Battery uses isothermal CAES underwater, but costly pressure tanks are still required to hold the compressed air.

Recently, in the literature and in industry, efficient, isothermal air compression concepts have been presented. Zhang et al. (2018) presented an enhanced cylindric piston expander by spraying water into the cylinder [36–38]. Chen et al. (2020) suggested an isothermal compressed air energy storage system with a roundtrip efficiency of 76% based on a hydraulic pump/turbine and spray cooling [39,40]. Bennett et al. (2021) proposed isothermal compressed air energy storage in saline aquifers near wind farms [41]. The AirBattery is an industrial isothermal CAES technology that stores air by isothermally replacing air with water, with an 81% round trip efficiency [42–45]. A pump forces water into the isothermal compressor tank. As the tanks fill with water, the air pressure rises, and the air is forced into one of the compressed air storage tanks. The electricity is then generated by pushing water through a hydropower turbine using compressed air. The high round trip efficiency of the system is the highest so far for an operational CAES system. However, the technology involves high costs of storing air in pressure tanks (estimated at 250 USD/kWh).

This work adds to the existing body of knowledge by suggesting a new approach that combines isothermal compression and the utilization of high-pressure compressed air storage tanks in the deep sea. The technology was named isothermal deep ocean compressed air energy storage (IDO-CAES). Herein, we show that IDO-CAES is particularly interesting for storing large amounts of energy in long-term storage cycles, such as seasonal and pluriannual cycles. The paper also estimates the costs of the technology and compares it to other energy storage solutions. Additionally, it provides the first the IDO-CAES global potential estimate. The proposed design was conceptualized by the authors.

2. Materials and Methods

Figure 2 depicts the methodological framework used in the article. It is divided into three stages. The IDO-CAES system is defined in Step 1. It details the components and the concept behind isothermal air compression and deep ocean long-term energy storage tanks, as well as a detailed description of the operation of the IDO-CAES system. Step 2 calculates the energy storage potential of the technology. It checks the solubility of air in the deep ocean and the air density at different depths to design the deep ocean tank. It then estimates the energy storage potential, power capacity and energy storage cost of the technology. Step 3 estimates the global potential of IDO-CAES.

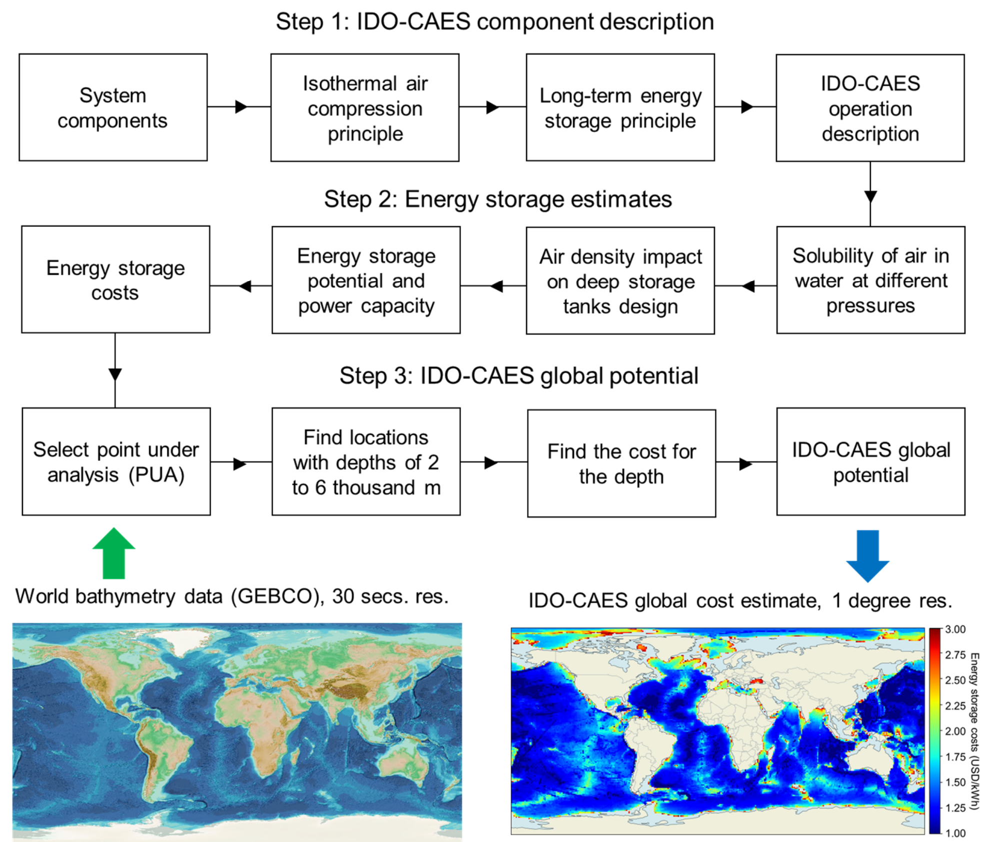

Figure 2. Methodological framework for IDO-CAES.

Isothermal Deep Ocean Compressed Air Energy Storage (IDO-CAES)

The isothermal deep ocean compressed air energy storage system presented involves the components in Figure 3 and is defined as follows: (1) the underwater transmission line connects the continental or island grids with the isothermal air compression ship (Figure 3a). (2) The isothermal air compression ship is located directly above the long-term energy storage tanks in the deep ocean, and it supports the compressed air pipeline and houses the isothermal air compressor and the pump/turbines. The ship's hull is designed to house the isothermal air compressor for 1 to 7 bar variations. (3) The compressed air pipeline transports compressed air in and out of the deep ocean long-term storage tanks. The pressure throughout the pipeline is similar to the pressure of the compressed air at the bottom of the ocean. There is, however, an increase in pressure with depth due to the high density of compressed air. The pipeline must be thick and made of resistant material (such as steel) to sustain the high compressed air pressures, mainly close to the surface. However, the pipeline cannot be made entirely of a rigid steel structure due to movements of the ship on the surface as a result of tides and waves. This flexible connection is added in the last few hundred meters of the pipeline, where the pressure inside the pipeline is similar to the pressure outside. Thus, a flexible pipeline can be installed. (4) The deep ocean compressed air long-term storage tanks are laid in the deep seabed (Figure 3a,c). They are partially filled with desert sand to prevent it from floating given the lower density of the compressed air compared to the surrounding water.

During storage mode, the compressed air is input through the top of the tanks, while seawater leaves through the bottom of the tank. This maintains the pressure inside the tank as the same as the pressure outside of the tank. This allows the storage tank to be made of cheap high-density polyethylene (HDPE) pipelines, resulting in very low energy costs and the possibility of using the technology for seasonal and pluri-annual energy storage. The compressed air permeation potential of HDPE under high-pressure settings is low, especially for HDPE (PE100) [46]. Instead of using the deep ocean tanks, depleted natural gas reservoirs can store the compressed air. (5) The isothermal air compressors are the link that allows the seawater pump/turbine to transform hydraulic pumping into isothermal air compression, and the isothermal decompression of the air into hydropower (Figure 3b). The isothermal compression system is divided into three or more stages depending on the depth of the long-term storage tanks. For example, the isothermal compression tanks levels proposed in this paper's case study vary from 358 to 50.4 bar, 50.4 to 7.1 bar (these tanks require special material and concrete reinforcement to sustain the high pressures) and 7.1 to 1 bar (which consists of the hull of the ship itself). When the hull is filled with seawater, the ship sinks. When the hull is filled with compressed air, the ship rises. (6) The multistage pump/turbine ternary unit is used both to pump water into the isothermal air compressor and to generate electricity by means of the isothermal decompression of the air. The multiple pump/turbine stages are connected to the same shaft and generator to reduce investment costs. Due to the large pressure variations during the storage and generation modes, the multiples stages can operate in series to increase the operation head or in parallel to reduce the operation head and increase the pump or generation flow. The turbine that pumps and generates electricity with the seawater in the ship's hull can be the ship's propeller, if adjusted to operate as a pump/turbine.

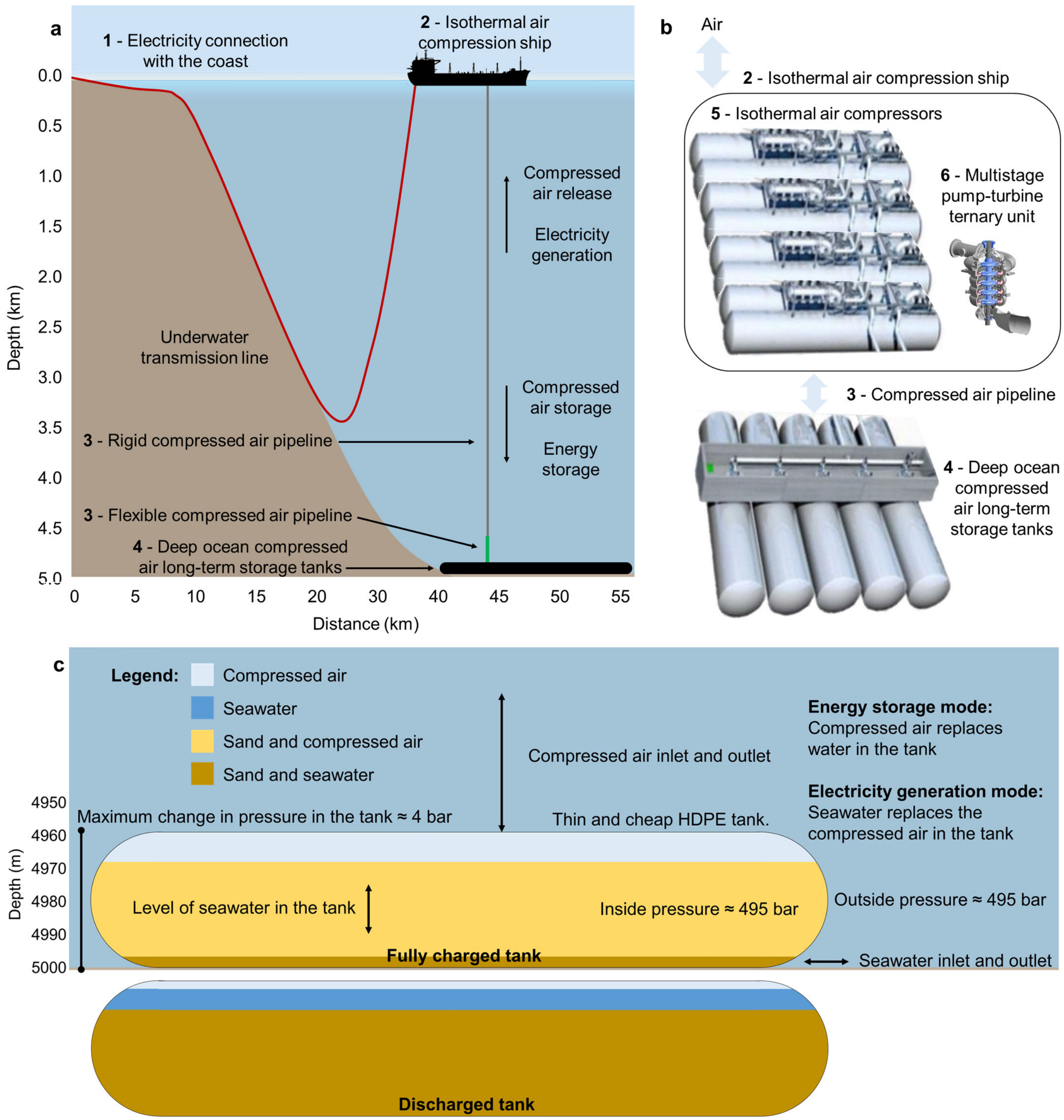

Figure 3. Isothermal deep ocean compressed air energy storage. (**a**) Technology overview, (**b**) main components and (**c**) deep ocean compressed air long-term storage tanks.

The main concept behind the IDO-CAES that makes it appropriate for long-term energy storage is presented in Figure 3c, and consists of using the very high pressure in the deep sea to allow a light and inexpensive HDPE tank to store large amounts of compressed air seasonally or inter-annually. The system stores energy by pumping superficial seawater into the isothermal air compressor. The compressed air flows to the deep sea storage tanks, where it replaces the seawater inside the tanks. During generation mode, the compressed air in the deep ocean tanks is replaced by seawater, and the compressed air flows to the isothermal air compression ship. In the isothermal air compressor, the compressed air replaces the seawater, and the seawater flows through the pump/turbine, generating electricity. Because the system's power costs are significant, it should be used to its full capability. The system's operating specialization is to store energy in seasonal or pluri-annual cycles in sync with battery systems that store energy in daily cycles, and IDO-CAES provides longer storage cycles.

Figure 4 presents an IDO-CAES plant's isothermal air compressor system at around 5000 m depth for compressing air at 1 atm to 495 bar. The system consists of 12 tanks and 6 turbines. Three different levels, for example, raise the air pressure from 1 atm to 7.1 bar (level 1), 7.1 to 50.4 bar (level 2) and 50.4 to 358 bar (level 3). The pressure drop in the vertical pipeline connecting the deep ocean tank and the isothermal compression/decompression system in the ship must be c, and equals considered 137 bar. This pressure loss is mainly due to the high hydraulic head of compressed air and the high density of the air in the pipeline. Two series of tanks and two pumps are required per level to guarantee a constant flow of pressurized air from one level to another. If not, there would not be an input or output of high-pressure air between different levels at all times. Another advantage of this arrangement is that, at each level, the pump/turbine head variation is divided into two. For example, in level 3, the head variation of one pump/turbine operates from 3138 m to 941 m, while the other pump/turbine at the same level operates from 941 m to 282 m. This results in a 70% generation head variation, which is possible with pump/turbines of variable speed. In each level and series, there are two tanks. The numbers of the tanks are divided into levels, series and pairs: for example, a tank of level 3, series 2 and pair 1 is named Tank 3.2.1. The number of pump/turbines is divided into level and series. For example, a pump/turbine of level 3 and series 2 is named pump/turbine 3.2.

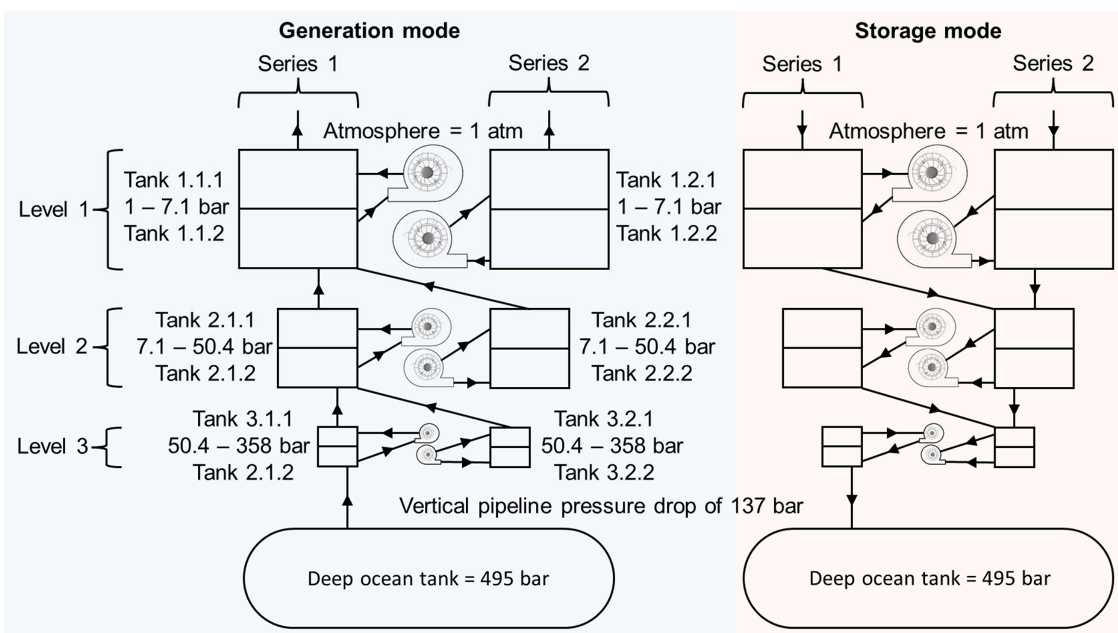

Figure 4. Isothermal air compressor system of an IDO-CAES plant with around 5000 m depth for compressing air from 1 atm to 358 bar.

The mechanism depicted in Figure 5 is the isothermal compressor/decompressor suggested in this article, representing level 3, series 1 and 2 and pairs 1 and 2. In level 3, there are 4 tanks and 2 pump/turbines. The water flowing through this level equals half the volume in the 4 system's tanks, pipelines and pump/turbines. In generation mode, compressed air enters Tank 3.1.2 from the vertical pipeline at 358 bar and pushes the water out of Tank 3.1.2, which rotates a turbine generating electricity and loads Tank 3.1.1 with a lower pressure (50.4 bar), displacing compressed air in Tank 3.1.1. When the compressed air input to Tank 3.1.2 is turned off, gas continues to flow from Tank 3.1.2 to Tank 3.1.1 and the pressure in Tank 3.1.2 reduces from 358 to 50.4 bar. The drop in the pressure differential causes the turbine's hydraulic generating head to decrease. The hydraulic generation head becomes so small after a specific pressure difference that electricity generation stops, and the residual compressed air flows to Tank 3.1.1. The procedure is restarted when the pressure in Tank 3.1.2 hits 50.4 bar, but the tanks swap roles. The power generated by each turbine cycle varies from 100 to 0%, but other turbines complement the lack of power generated. A battery or ultracapacitor can be used to guarantee a constant power supply from the system. During storage mode, the pump displaces the water in Tank 3.1.1, allowing compressed air to enter the tank at a low pressure (50.4 bar). The pumps are powered by electricity, which raises the water pressure and fills Tank 3.1.2. As there is no compressed air leaving the tank, the pressure in tank 3.1.2 climbs from 50.4 to 358 bar. When the pressure in Tank 3.1.2 reaches 358 bar, compressed air is evacuated from the tank until it is filled with water. When Tank 3.1.2 is full of water, the method is repeated, but the tanks' roles are reversed.

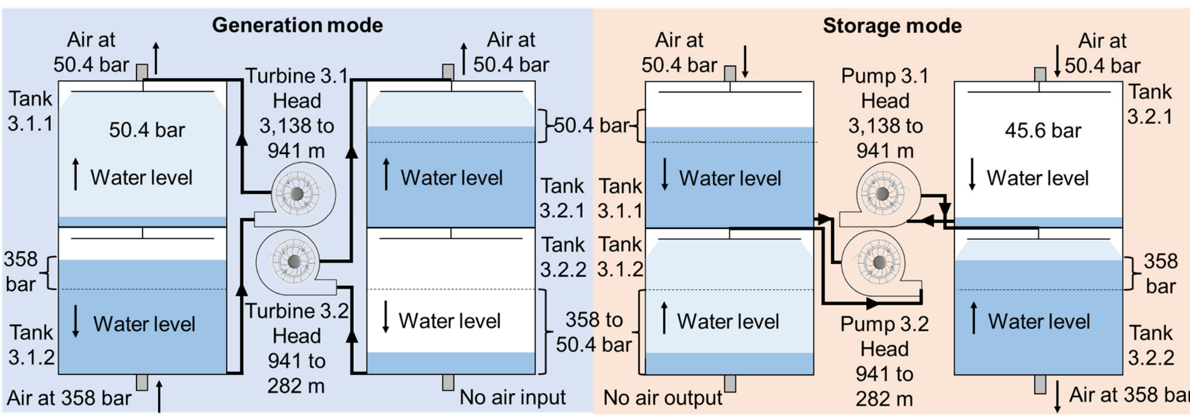

Figure 5. Operation of the isothermal air compressor at level 3, displaying the 4 phases of the storage and generation modes.

It is necessary to determine the weight and buoyancy equilibrium of the tanks without saltwater at various depths to establish the minimal required amount of sand in the deep ocean storage tanks and avoid floating. This article proposes that desert sand is the most suited material for counterbalancing the buoyancy potential of compressed air. It is inert and cheap, and has appropriate porosity to store air and seawater. Equation (1) is applied to design the deep ocean compressed air long-term storage tanks.

$$V \times \rho_{SW} < V_S \times \theta \times \rho_S + V_A \times \rho_A + M \quad (1)$$

where V is the volume of the tank; V_S is the sand volume; ρ_S is the sand density, assumed to be 1900 kg/m^3; ρ_{SW} is the seawater density, assumed to be 1028 kg/m^3; and θ is the porosity of sand, assumed to be 60%. V_A is the compressed air volume; ρ_A is the compressed air density, which varies with depth; and M is the pipeline mass, which is neglected in this paper. The density of the air was taken from [47]. The oceanic pressure at different depths was taken from [48].

As the energy is stored by displacing seawater in deep ocean tanks with compressed air, the energy storage of IDO-CAES is equivalent to the energy required to displace deep seawater, and can be estimated with Equation (2).

$$E = (V_A - V_D) \times \rho_{SW} \times g \times (d - h_L) \times e \quad (2)$$

where E is the energy storage potential in the deep ocean tanks; V_A is the volume of compressed air in the deep ocean tanks; V_D is the volume of air dissolved in seawater in the deep ocean and the ship; ρ_{SW} is the density of seawater above the deep ocean tanks, assumed to be 1028 kg/m^3; d is the depth of the deep ocean tanks; g is the acceleration of gravity (9.81 m/s^2); h_L is the head loss resulting from the column of compressed air in the vertical pipeline, which connects the deep ocean tanks and the ship; and e is the round trip efficiency of the system, assumed to be 70%, as the air compression and decompression are performed by isothermal processes.

3. Results

Equation (1) is applied to estimate the amount of sand required to keep the pipeline on the bottom of the ocean. Figure 6a shows the air density variation, along with depth. The density of air rises significantly with depth, reaching densities of 128 kg/m^3 at 1000 m, 484 kg/m^3 at 5000 m and 655 kg/m^3 at 10,000 m [47]. Figure 6b shows the required volume of sand at different depths. Figure 6c shows the cross-section of the tanks at depths of 1000, 5000 and 10,000 m.

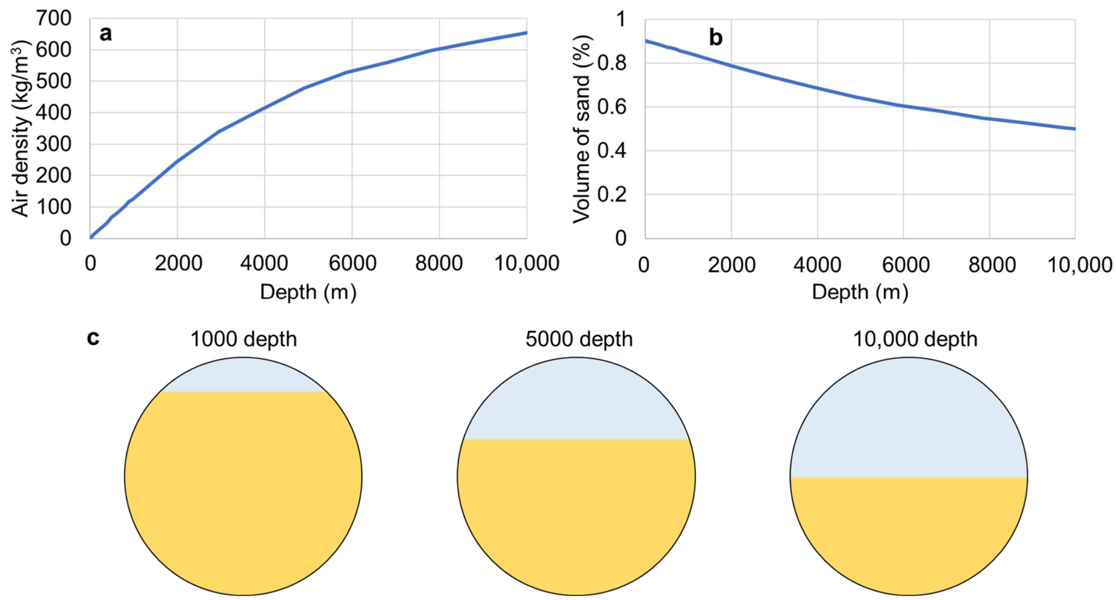

Figure 6. Weight balance at different depths. (**a**) Air density [47]; (**b**) the required volume of sand at different depths; (**c**) a cross-section of the tanks at 1000, 5000 and 10,000 m depth.

It is important to know the solubility of air in pressurized seawater in order to estimate the amount of air dissolved in the superficial and deep seawater in the storage process, and, thus, the energy lost due to the reduction of compressed air in the system. The mixing of saltwater with compressed air makes sense only if the solubility of air in water is low, because the air dissolved in water would be squandered in the ocean. Air has low solubility in water. For example, the partial pressure of oxygen at 500 bar and 0 °C is 12.8 g/kg in seawater [49], while the partial pressure of nitrogen in the same conditions is 7.6 g/kg [50], and for CO_2, it is 100 g/kg (note that the concentration of CO_2 in the air is very low). At depths of 4000 m, this accounts for a compressed air loss of 2.5%. However, the deep sea already has a high concentration of N_2 and O_2, and the losses due to solubility would be significantly smaller. In addition,, the concentration of N_2 and O_2 in the deep ocean varies significantly from location to location due to the predominant ocean currents, which increases the challenge of estimating the losses due to solubility. Thus, this paper neglects air losses through the solubility of seawater.

Figure 7 presents the IDO-CAES energy storage estimation, with Figure 7a showing the change in pressure in the vertical pipeline. Each line corresponds to a different deep ocean tank depth, the maximum depth being 1000, 2000, 3000, 4000, 5000 and 6000 m. The change in pressure in the vertical pipeline is estimated by: (i) assuming that the compressed air pressure in the deep ocean tank equals to the ocean pressure surrounding it, and (ii) removing 10 m of compressed air from the bottom of the pipeline, thus reducing the pressure of the air column until the pipeline reaches the ship at the surface. Figure 7b shows the pressure difference between the compressed air in the vertical pipeline and the pressure of the ocean surrounding the pipeline at the same depth. The compressed air density at high pressures is not good for IDO-CAES because the seawater density becomes similar at 1028 kg/m^3, and the head loss in the vertical pipeline increases. Figure 7c shows the compressed air pressure in the ship and head loss, and Figure 7d represents the energy storage capacity of the system at different depths. Equation (2) is applied to the energy storage capacity of the system at different depths. The deep storage tanks used to estimate the energy storage potential consist of 200 pipes side by side, 5 km long and 40 m in diameter, which results in a volume of 1.256 km^3. This results in an energy storage potential of 1.4 TWh and 28 days of electricity generation at a 2 GW power capacity, with a system depth of 1000 m; and 6.6 TWh and 137 days of electricity generation at a 2 GW power capacity, with a system depth of 5000 m. This is equivalent to 15% and 68% of the annual electricity consumption of Hawaii, respectively, which is 9.6 TWh [51].

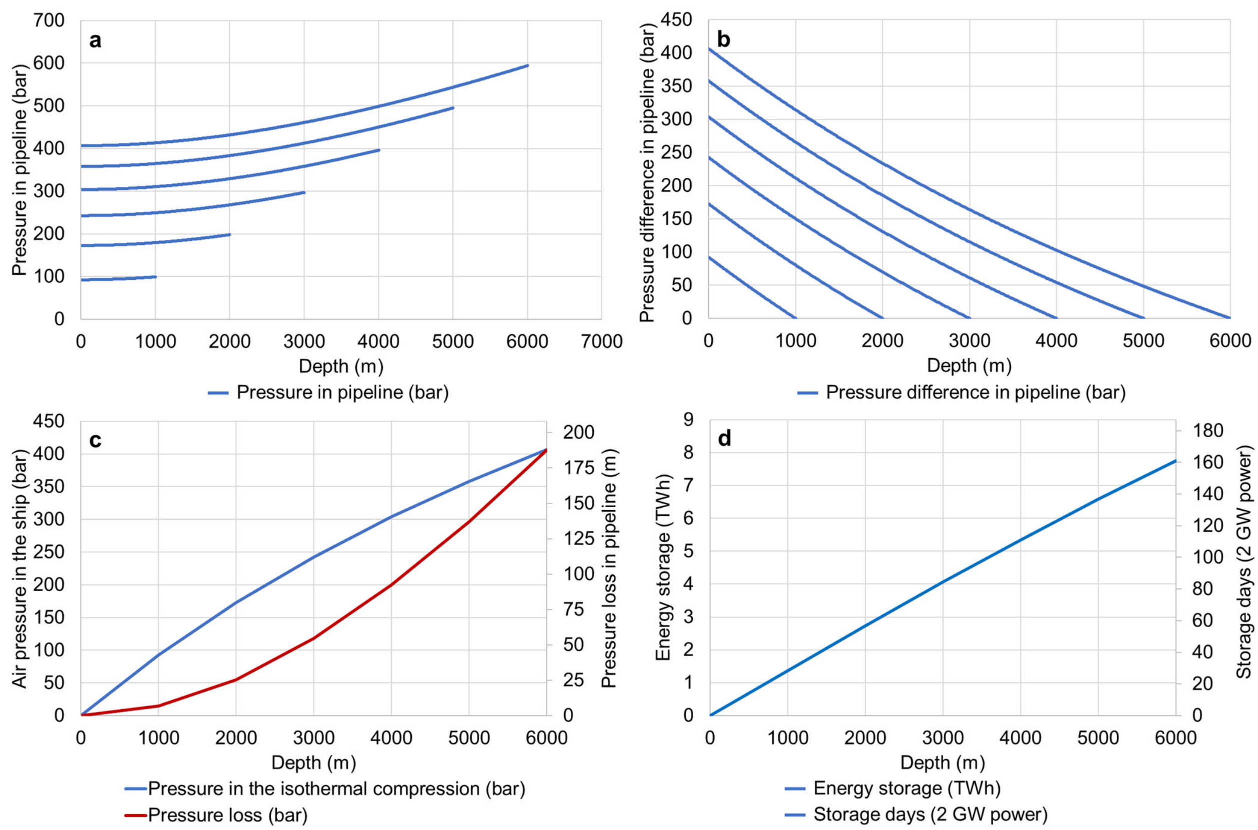

Figure 7. IDO-CAES energy storage estimation, showing (**a**) the pressure of the compressed air in the vertical pipeline, (**b**) the pressure difference between the compressed air pipeline and the ocean, (**c**) the compressed air pressure in the ship and head loss, and (**d**) the energy storage capacity of the system in the deep ocean.

Table 1 presents the isothermal air compressor design proposed in this study, with a description of the pressure variation, pressure increase, relative volume, and the tank volume where the compressed air pressure is constant. Figure 8 presents the isothermal air compressor power description, including the hydraulic head variation in the arrangement proposal of the three tanks. As can be seen, Tank 1 has a very high volume but a small generation head, Tank 2 has a medium volume and generation head and Tank 3 has a small volume but a high generation head (Figure 8a). The resulting energy storage and generation of the three isothermal air compressor tanks are similar, as shown in Figure 8b.

Table 1. Isothermal air compressor design description.

Tanks	Tank Description	Pressure (bar)	Pressure Increase (bar)	Relative Tank Volume	Constant Air Pressure Volume (%)
1	Tank 1 consists of a ship's hull adapted as an isothermal air compressor. The pump/turbine can be divided into 2 stages, with a head of 5 m, that operate in series when the pressure is high and in parallel when the pressure is low.	1–7.1	6.1	50.41	14.1
2	Tank 2 consists of an isothermal air compressor. The pump/turbine can be divided into 5 stages, with a head of 40 m, that operate in series when the pressure is high and in parallel when the pressure is low.	7.1–50.4	43.2	7.1	14.1
3	Tank 3 consists of an isothermal air compressor. The pump/turbine can be divided into 2 stages, with a head of 500 m, that operate in series when the pressure is high and in parallel when the pressure is low.	−50.4–358	307.6	1	14.1

Figure 8 presents the power description of the IDO-CAES in series, including the hydraulic head variation in the arrangement proposal of the three tanks. As can be seen, System 1 has the highest volume (86.2%) but, a small generation head (62.2 m to 5.6 m); system 2 has a medium volume (12.1%) and generation head (440.6 m to 39.7 m); and system 3 has a small volume (1.7%), but a high generation head (3137.5 m to 282.4 m), as shown in Figure 8a. The resulting electricity generation potential shared between the three systems is calculated with Equation (2) and shown in Figure 8b.

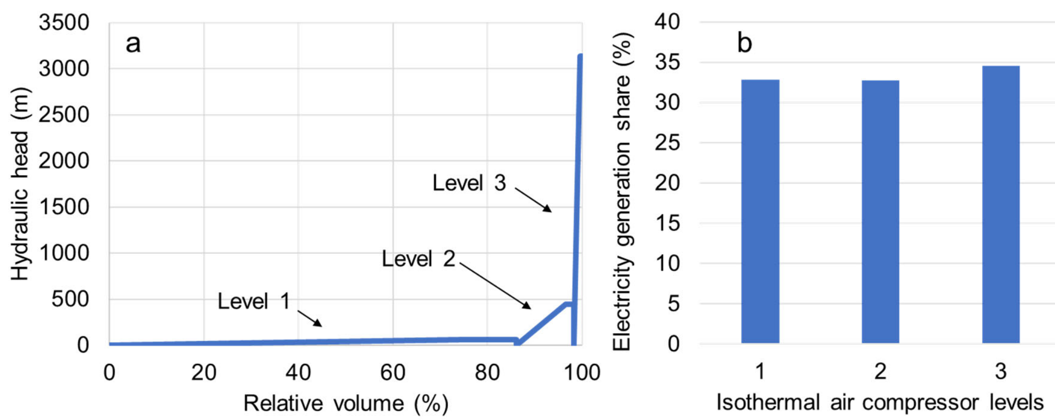

Figure 8. Isothermal air compressor power description. (**a**) Hydraulic head variation for the arrangement proposal of the three tanks, (**b**) power supply and storage share between the three isothermal air compressor tanks.

3.1. IDO-CAES Investment Cost Estimation

Table 2 shows the investment cost estimate for an IDO-CAES system with compressed air storage tanks at a depth of 5000 m to store energy from floating wind power plants. Figure 9 shows the IDO-CAES energy storage cost variation according tp\o depth in USD/kWh. A significant investment in IDO-CAES can substantially reduce these costs. As the proposed IDO-CAES project stores energy from an existing floating wind power plant, the costs of electrical components such as a transmission cable, electrical protection and substation are not considered. Maintenance costs are also not considered. Environmental variables can significantly influence the cost components, and are not included in this paper. Maintenance costs are not included in investment costs, but can be assumed to be 5% of the investment costs per year. Figure 10 presents the energy storage costs and discharge times with different storage and power capacities.

Table 2. Investment cost estimation for IDO-CAES components with 6.6 TWh storage capacity and 1 GW installed capacity.

Component	Description	Cost
Isothermal compression ship	The ship and anchor support the equipment required to perform the isothermal compression.	USD 0.1 B
Isothermal air compression	Isothermal compression equipment required for 1 GW of energy storage and power production capacity [52].	USD 1 B
Compressed air vertically pipeline	A steel conduit, 5 km long, is required to link the ship with the deep ocean tanks [53]. To prevent saltwater corrosion, the pipeline's cost is raised by two.	USD 0.5 B
Deep ocean pipe	200 HDPE pipes, 5 km long, with 40 m diameter and 1.256 km^3 of volume. We extrapolated the costs in [54].	USD 1.92 B
Deep ocean pipe sand	USD 1 per ton of desert sand [55]. It is estimated that 1.5 billion tons are required. The density is 1900 kg/m^3. Alternatively, sand might be taken from the deep sea near the storage site.	USD 1.54 B
Construction	50% of the equipment costs.	USD 1.73 B
Total project cost	-	USD 6.78 B
Energy storage costs	IDO-CAES with 6.6 TWh energy storage capacity.	1.03 USD/kWh
Power capacity costs	Installed power generation capacity: this comprises the expenses of the ship's isothermal compression, and the vertically pipeline for compressed air.	1600 USD/kW

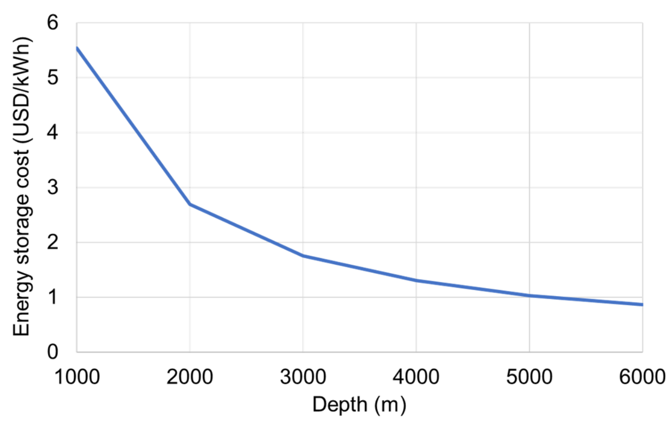

Figure 9. IDO-CAES cost of energy storage (USD/kWh) at different depths.

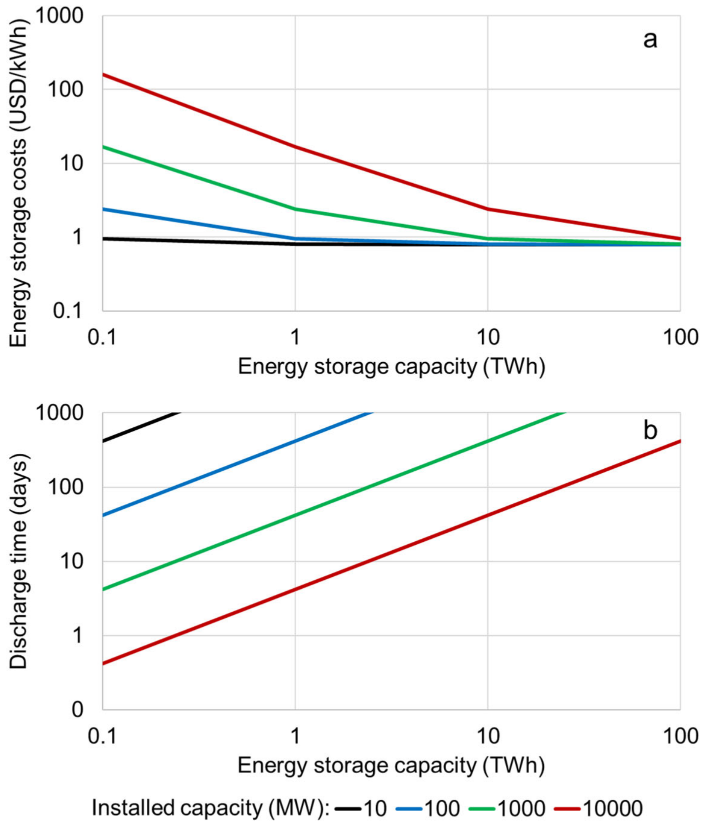

Figure 10. IDO-CAES systems at 5000 depth. (**a**) Energy storage cost and (**b**) discharge time with different installed capacities.

3.2. IDO-CAES Global Potential

The global potential of IDO-CAES was assessed with a computational model. Bathymetry data from GEBCO [56] with 30″ resolution (equivalent to 900 m at zero latitude) was used. The potential is proportional to the ocean depth. The represented depth started from 2000 m to improve the visualization of the results. Figure 11 presents the global potential of IDO-CAES. Figure 9 presents the relation between the ocean depth and the storage cost. To enhance the presentation of the data in Figure 11, each 30″ resolution pixel with the highest depth was downscaled to one degree of resolution. The best regions of IDO-CAES were found to be islands and the coasts of Australia, Philippines, Japan, Indonesia, the USA, Chile, Mexico, Ecuador, Colombia, Peru, Jamaica, Cuba, Honduras, Brazil, Guatemala, Oman, Madagascar, Somalia, South Africa, Ghana, the Ivory Coast and Portugal.

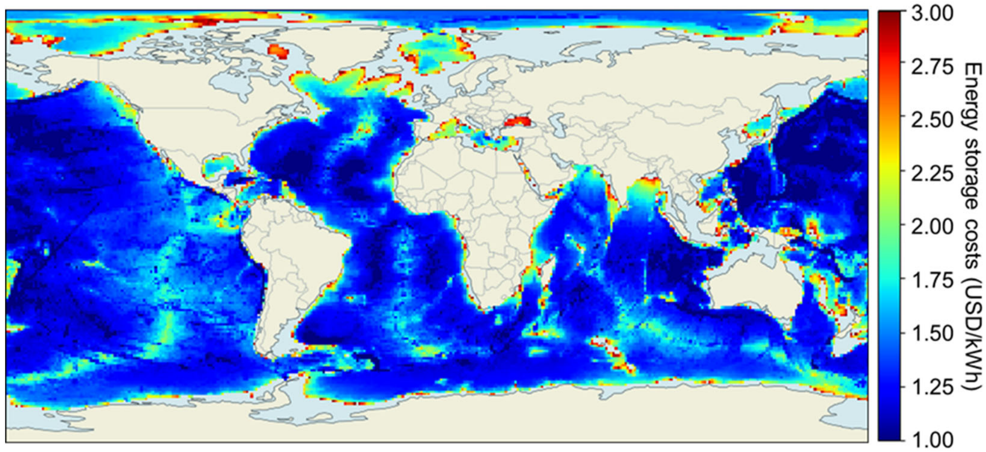

Figure 11. Global potential for IDO-CAES.

3.3. Operational Proposal for IDO-CAES

We projected an IDO-CAES with 1 GW and 3 TWh capacity, as well as a floating offshore wind plant with 3.1 GW installed capacity and a battery to meet short-duration energy storage needs (the operation of the batteries is not represented in the case study) close to Honolulu, Hawaii, USA. The offshore wind power outline utilized data from [57] at 21.1954 latitude and −158.9862 longitude in 2020. The annual electricity consumption of Hawaii is 9.6 TWh [51,58]. The operational proposal for IDO-CAES is presented in Figure 12. The IDO-CAES plant stores energy mostly in monthly and seasonal cycles. This is acceptable since the installed capacity (GW) cost is high, while the cost of energy storage is cheap. (GWh).

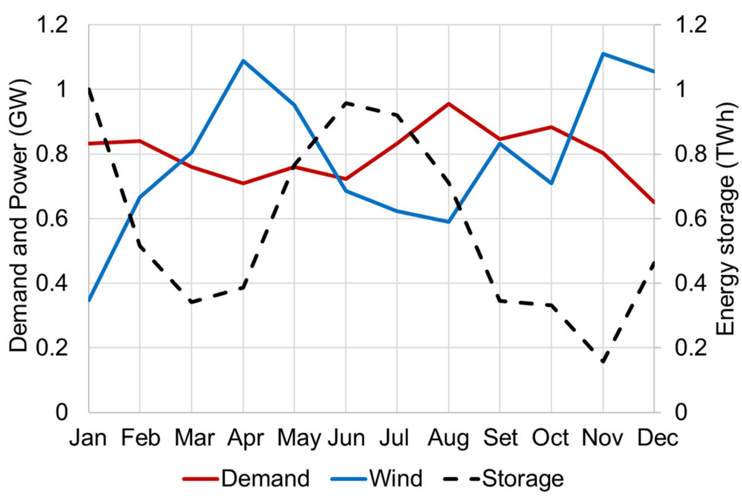

Figure 12. Operational case study for IDO-CAES to store solar energy for Hawaii, containing electricity demand, wind power and energy storage.

4. Discussion

The IDO-CAES was placed far away from areas with demand for electricity. Therefore, it is restricted to particular scenarios. Table 3 shows the scenarios in which IDO-CAES could be applied.

Table 3. Possibly viable scenarios for IDO-CAES systems.

Scenarios	Description
Seasonal storage	The only alternatives for seasonal electrical storage are PHS and synthetic fuels, such as green H_2 and ammonia. IDO-CAES is another option.
Areas by the coast	Coastal areas with weekly or seasonal storage demand without viable pumped-storage potential could benefit from ISO-CAES. Note that the project cost increases with distance to the deep ocean due to underwater transmission costs.
Islands	The continental plates are short for islands. This allows for the construction of an IDO-CAES plant only a few kilometers from an island.
Offshore wind power	Wind energy can be stored with IDO-CAES because it is suitable for weekly storage cycles. Additionally, offshore wind power plants would reduce the distance from the IDO-CAES project to the existing grid, as both are located offshore.
Floating offshore wind power for hydrogen generation	The potential of IDO-CAES for storing energy from floating offshore wind power plants is great. This is because a floating offshore plant can be installed beside an IDO-CAES plant.
Ocean thermal energy conversion (OTEC)	The potential of IDO-CAES for storing energy from OTEC is large. This is because an OTEC plant can be installed beside an IDO-CAES plant.
Deep sea mining	A significant amount of energy will be demanded by deep sea mining projects in the future. IDO-CAES can provide energy storage for deep sea mining projects.

IDO-CAES plants are a viable alternative for generating or storing a constant amount of energy in weekly, monthly or seasonal cycles due to their cheap energy storage cost (MWh) and high power cost (MW), whereas batteries can offer hourly and daily energy storage. Table 4 compares the major features of IDO-CAES to those of other mechanical and electrochemical energy storage technologies. The expected lifetime of IDO-CAES systems is 30 years, with some equipment, such as deep-water tanks, having a longer lifespan. The costs of long-term storage with this technology could be further reduced by using depleted natural gas reservoirs instead of the deep ocean tanks, as they can store compressed air. In these cases, CAES plants could be installed on land. Seesaw, another technology proposed by the authors of this paper [59], has been proposed to store energy for weeks or months. However, IDO-CAES has been proposed for storing energy seasonally. In [60], a comparison of different energy storage systems is provided.

Table 4. Comparison of IDO-CAES costs with other technologies (cost data from [4,60–64]).

Technology	Capacity (MW)	Energy Storage Cost (USD/kWh)	Installed Capacity Cost (USD/kW)	Round Trip Efficiency (%)
Pumped hydropower storage (PHS)	100–10,000	2–50	400–1000	70–85
Batteries (lithium-ion)	1–500	125	250	95–90
Hydrogen (salt cavern)	1–2000	0.2–10	500–700	30–60
Seesaw [59]	1–100	10–50	800–1500	80
IDO-CAES	100–2000	1–10	1500–3000	70

IDO-CAES has a considerably lower environmental footprint when compared to batteries and pumped hydro storage. The environmental impact of IDO-CAES is restricted to the extraction and return of deep seawater from the deep ocean tanks, respectively. These processes should be carried out with care to minimize their impact on the aquatic fauna and flora. Possible impacts of the increase in solubility of oxygen, nitrogen and CO_2 in the deep sea need to be evaluated with care. Mitigation measures, such as nets, could be used to prevent animals from moving into the isothermal compressors.

Currently, the world is undergoing a shortage of high-quality river bed sand [65]. The sand required for IDO-CAES is desert sand, which has high porosity and permeability. As there is a high availability of desert sand, and its impacts are significantly smaller than riverbed sand, resource availability is not a concern for the proposed technology.

In sites near the tropics, the temperature difference between superficial and deep seawater tends to be more than 20 °C. IDO-CAES can be combined with oceanic thermal energy conversion (OTEC), where the ambient air entering at 32 °C is compressed and cooled by cold deep-sea water at 3 °C, reducing the energy consumed while compressing the air. Then, the cold compressed air (at 3 °C) coming from the long-term energy storage tank is warmed up to 30 °C using warm, superficial waters. The combination of IDO-CAES and OTEC does not result in a positive overall energy balance from the system, but it may boost the overall system efficiency of the system.

One aspect of the isothermal CAES technology that has not yet been considered is that the CO_2 dissolved in the water can be easily separated after the decompression stage. In other words, the proposed technology can also be used as a technology for "Direct Air Capture" of CO_2, with little added cost. The captured CO_2 can then be turned into synthetic fuels using H_2 and electricity. In this way, IDO-CAES can provide energy storage services and produce e-synthetic fuels.

With weekly, monthly and seasonal energy storage cycles, this article contends that IDO-CAES might cover the present gap in decentralized energy storage solutions. IDO-CAES, batteries, PHS, ammonia and hydrogen are all depicted in Figure 13. This graph focuses on long-term energy storage options [66] as well as the limitations of batteries. Given the need for a ship on the surface and a connection with the deep ocean, we suggest that a minimum viable IDO-CAES prototype should have at least 100 MW. The studies referenced in [67–73] can be considered for further information on technologies with short-term storage cycles. This diagram can help decision-makers and energy planners to comprehend the potential costs and benefits of this storage system in comparison to other options.

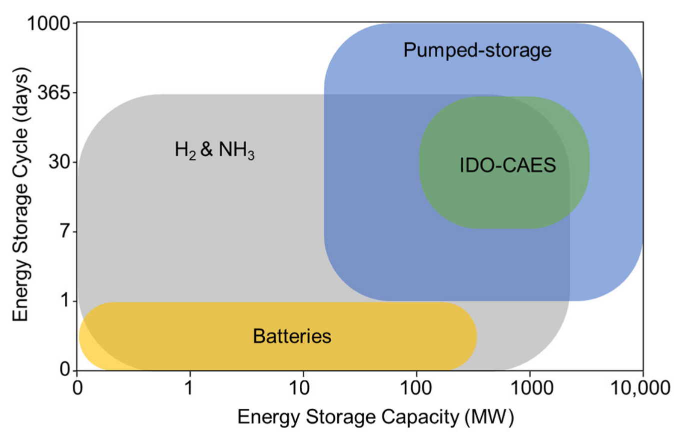

Figure 13. Long-term energy storage technologies (IDO-CAES, hydrogen, ammonia and PHS) are compared against short-term energy storage (batteries), with their relative energy storage cycles and installed capacities shown.

Future work regarding IDO-CAES will involve an electrical study of voltage levels and generated power, and the isothermal compression will be tested in a computational fluid dynamics model or in a real-life prototype to provide a more precise estimate of the system's efficiency in different operational scenarios.

5. Conclusions

This paper presents an innovative energy storage technology to fill the gap for long-term storage options (weekly, monthly, seasonal and pluri-annual). The cost of IDO-CAES varies between 1500 to 3000 USD/kW of the installed capacity and 1 to 10 USD/kWh of the energy storage cost, with a capacity from 100 to 10,000 MW. The greater the ocean's depth, the lower the cost of the project. The best regions of IDO-CAES are islands and the coasts of Australia, the Philippines, Japan, Indonesia, the USA, Chile, Mexico, Ecuador, Colombia, Peru, Jamaica, Cuba, Honduras, Brazil, Guatemala, Oman, Madagascar, Somalia, South Africa, Ghana, the Ivory Coast and Portugal.

Battery costs have been decreasing considerably in the last decade. IDO-CAES is intended to supplement batteries, providing long-term and cheap energy storage. The combination of these technologies results in low energy storage costs (USD/kWh) and power capacity costs (USD/kW). IDO-CAES stores and generates energy in long-term cycles, and batteries store energy in storage cycles. This hybrid system ensures that the IDO-CAES will operate at its maximum capacity factor.

CAES has received much attention in the research field, but there are only a few industrial applications. The possibility of compressing air with isothermal air compressors and electricity storage efficiencies higher than 80% makes CAES an interesting alternative for energy storage in the future, particularly for long-term energy storage.

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Abbreviations

VRE—variable renewable sources; IDO-CAES—isothermal deep ocean compressed air energy storage; PHS—pumped-hydro storage; CAES—compressed air energy storage; UWCAES—underwater compressed gas energy storage; HDPE—high-density polyethylene; GEBCO—the general bathymetric chart of the oceans; OTEC—oceanic thermal energy conversion.

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