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Buoyancy Energy Storage Technology: An energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression

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ABSTRACT

The world is undergoing a substantial energy transition with an increasing share of intermittent sources of energy on the grid such as wind and solar. These variable renewable energy sources require an energy storage solution to allow a smooth integration of these sources. Batteries can provide short-term storage solutions. However, there is still a need for technologies that can provide weekly energy storage at locations without potential for pumped hydro storage. This paper presents innovative solutions for energy storage based on "buoyancy energy storage" in the deep ocean. The ocean has large depths where potential energy can be stored in gravitational based energy storage systems. The deeper the system, the greater the amount of stored energy. The cost of Buoyancy Energy Storage Technology (BEST) is estimated to vary from 50 to 100 USD/kWh of stored electric energy and 4,000 to 8,000 USD/kW of installed capacity. BES could be a feasible option to complement batteries, providing weekly storage cycles. As well as from storing energy, the system can also be used to compress hydrogen efficiently.

1. Introduction

Island grids usually operate a relatively expensive energy system due to the complications related to (i) maintaining energy security, including the logistics of importing and storing fossil fuels [1,2]; (ii) the requirements for meeting electricity demand reliably at any time, which leaves the system with challenges related to the provisioning of large back-up capacity and dealing with emissions and techno-economic burdens of part-load operation [3–6]; and (iii) low electricity demand, which reduces the options for employing an economic base load electricity generation system [7]. The possibility of generating electricity with variable renewable energy (VRE) sources, such as wind and solar, has considerable potential for lowering electricity costs in small islands and micro-grids [8,9]. However, VRE requires a supplementary flexibility solution due to the intermittency and seasonal variation in supply [10]. In addition, the electricity demand in small grids often varies a lot depending on holiday seasons and weather conditions [11–13].

Electrical energy storage (EES) alternatives for storing energy in a grid scale are typically batteries and pumped-hydro storage (PHS). Batteries benefit from ever-decreasing capital costs [14] and will probably offer an affordable solution for storing energy for daily energy variations or provide ancillary services [15–18]. However, the storage capability of batteries in a weekly cycles may never become economically viable, due to the high cost of stored energy (USD/MWh), and in some cases, a high rate of losses and/or self-discharge per day [19]. Moreover, the large-scale deployment of batteries in mobility applications and power systems raises questions related to the resource's availability and sustainability of extensive use of materials for batteries [20,21]. Mountainous regions have the potential for long-term, seasonal energy storage with pumped hydro storage [22–26] or mountain gravity energy storage [27]. There is currently no viable technology in the market that offers affordable weekly energy storage in the ocean, coastal areas, or islands without mountains. This paper argues that this gap can be filled with Buoyancy Energy Storage Technology (BEST). BEST is an energy storage technology that deploys an electric motor/generator for

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Nomenclature

D	Drag force
ρ_s	Density of sea water
u	Velocity of the buoyancy recipient
c_d	Drag coefficient
A	Frontal area of the buoyancy recipient
P	Power
v	Lowering or rising buoyancy recipient velocity
V	Volume of compressed air in the buoyancy recipient
ρ_c	Density of the compressed gases
m	Mass of the BEST system
g	Acceleration of gravity
e	BEST system efficiency
E	BEST system energy stored in the system
d	Depth of the buoyancy recipient

storing energy by lowering a compressed gas recipient in locations with deep sea floors and generating electricity by allowing the compressed gas recipient to rise though the water, as shown in Fig. 1.

Underwater gravity energy storage has received small attention, with no commercial-scale BEST systems developed to date [28]. The work thus far is mostly theoretical and with small lab-scale experiments [29]. Alami et al. [30–32] tested an array of conical-shaped buoys that were allowed to rotate. The buoys were also treated with a helical groove pattern to promote a certain spin rate as the buoy array ascended. The reasoning for this arrangement was to reduce drag during fast ascents (1.5 m/s). Bassett et al. [33–35] tested spherical buoys at similar velocities, which results in round trip efficiencies of 90%. BEST for great depths has also been proposed [29,36]. In these proposals, balloons or structures filled with lighter-than-air gases, such as hydrogen, are raised and lowered to release and store energy, respectively. Samadi-Boroujeni [37] have proposed to use underwater gravity energy storage to isothermally and efficiently (>50%) store compressed air for later electricity generation.

A similar energy storage proposal that has been receiving substantial attention is underwater compressed air storage. It consists of a fixed storage site on the deep sea and a compressor that sends pressurized air to the storage site [38]. The main challenge with this proposal is the requirement of a riser that connects the underwater storage site to the surface, which can sustain the high difference in pressure along the depth of the tunnel. Several research projects have been investigating this technology [39–43], and an existing project has been implemented recently in Toronto, Canada [44].

Looking at gravitational energy storage above ground, there are several companies that are investing in gravitational energy storage.

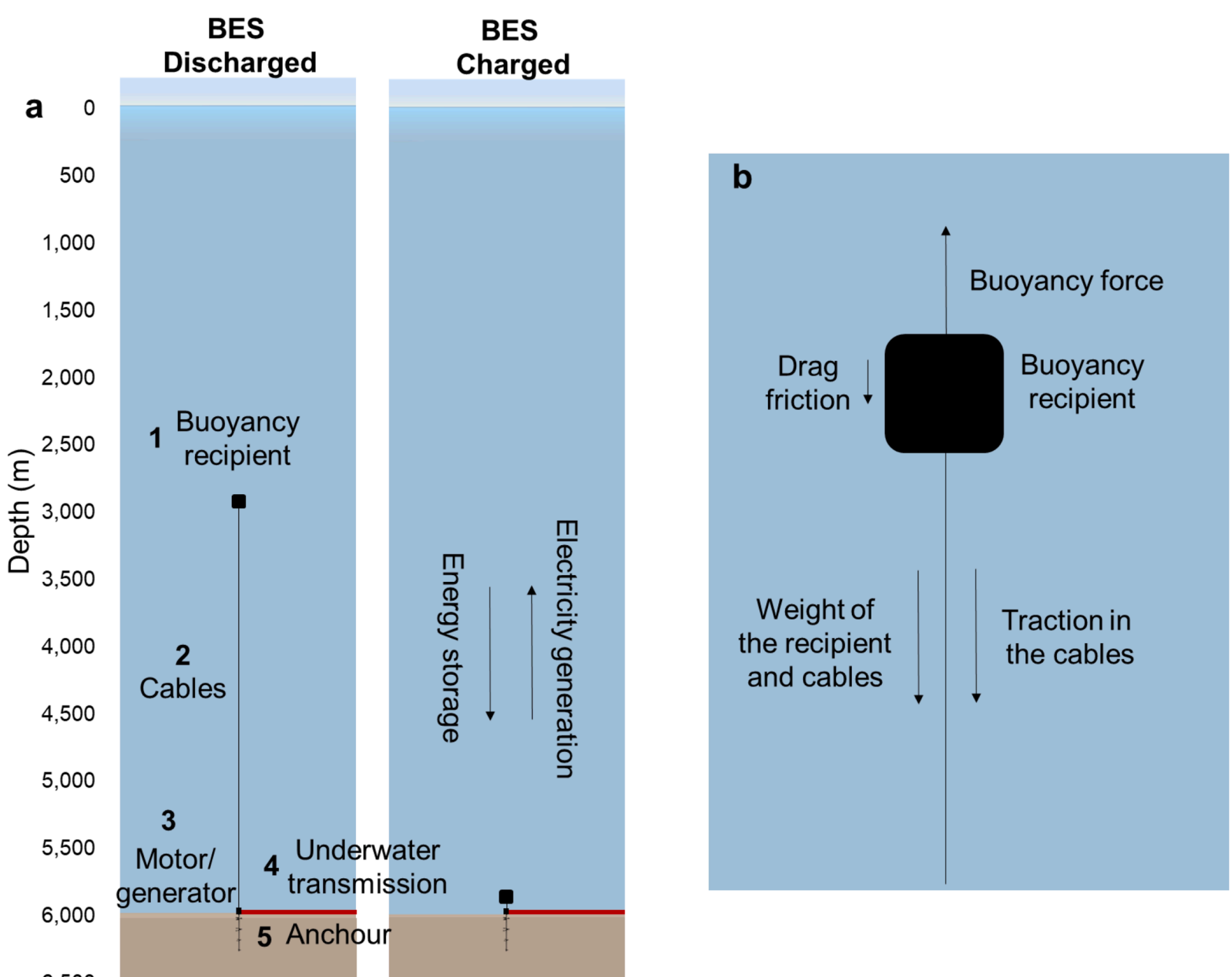


Fig. 1. Buoyancy Energy Storage, (a) the sketch of the system and the main components, (b) presents the forces exerted in the buoyancy recipient.

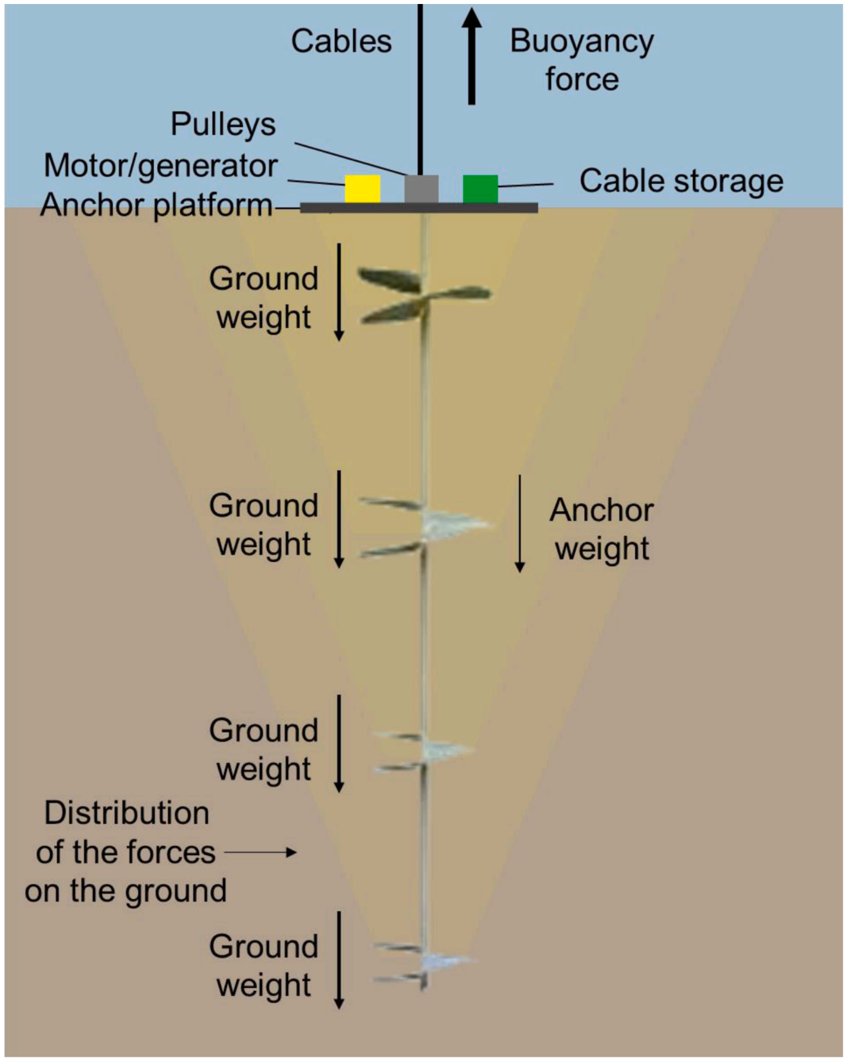


Fig. 2. Representation of the anchor of a BEST system.

Energy Vault consists of building a head difference with massive concrete blocks. The disadvantage of this technology is that the head difference between the upper and lower storage sites is low [45,46]. Another solution proposes to dig a well in the ground to create the required head for storing potential energy. However, the excavation costs of the well would considerably increase the costs of the plant [47–51]. There are also proposals for using train tracks to carry a concrete mass from the lower to the upper storage site [52–55]. A vertical descent might results in smaller costs and energy losses as proposed in [27,56]. Reference [57] presents a review of EES technologies, including gravel energy storage technology [58].

The main contributions of this paper to the literature are to estimate the costs of BEST with air and hydrogen as compression gases and the to estimate the global potential for the technology. The paper shows that deep ocean gravitational energy storage technologies are particularly interesting for storing energy for offshore wind power, on coasts and islands without mountains, and as an effective approach for compressing hydrogen. There is a lack in the literature of a comprehensive cost-benefit analysis of the global potential assessment of BEST and a discussion of the main benefits and challenges involved in the technology, which is included in this paper. This paper analyses the techno-economic feasibility of such technology in comparison to alternative EES systems. Furthermore, by applying a GIS-based analysis, this study investigates the global potential of BEST, which provides the first-of-its-kind assessment of the potential contribution of such storage technology. The design proposed in this paper has been developed by the authors and is considerably different from what has been proposed in the literature. We explain these differences in the discussion section.

1.1. Buoyancy Energy Storage Technology (BEST)

The buoyancy energy storage system proposed in this paper consists of the components presented in Fig. 1 and described as follows: 1) The buoyancy recipient can be a series of balloons or tanks that hold a compressed gas that contributes to a smaller density than the water, which results in a buoyancy force that is used to store or generate electricity. The compressed gases analysed in this paper are air and hydrogen. Air because it is abundant and free and hydrogen because its density is very low, even at pressures up to 600 bar; 2) Cables connect the anchor and the generator to the buoyancy recipient. They must have high tensile strength to sustain the buoyancy force. To distribute the forces into more cables, pulleys are applied. The cable is stored in a cylinder attached to the motor/generator when the buoyancy recipient is lowered. The pulleys also contribute to increasing the speed of the cables and lowering the forces applied to the motor/generator. The average velocity of the rising buoyancy recipient should be below 10 mm/s to significantly reduce losses from drag forces [28]. Due to the pulleys, the velocity of the cables can be much higher, for example, 1 m/s. The cost of the cables can be a limiting factor for BEST systems due to their long length and the very high forces they must sustain; 3) The

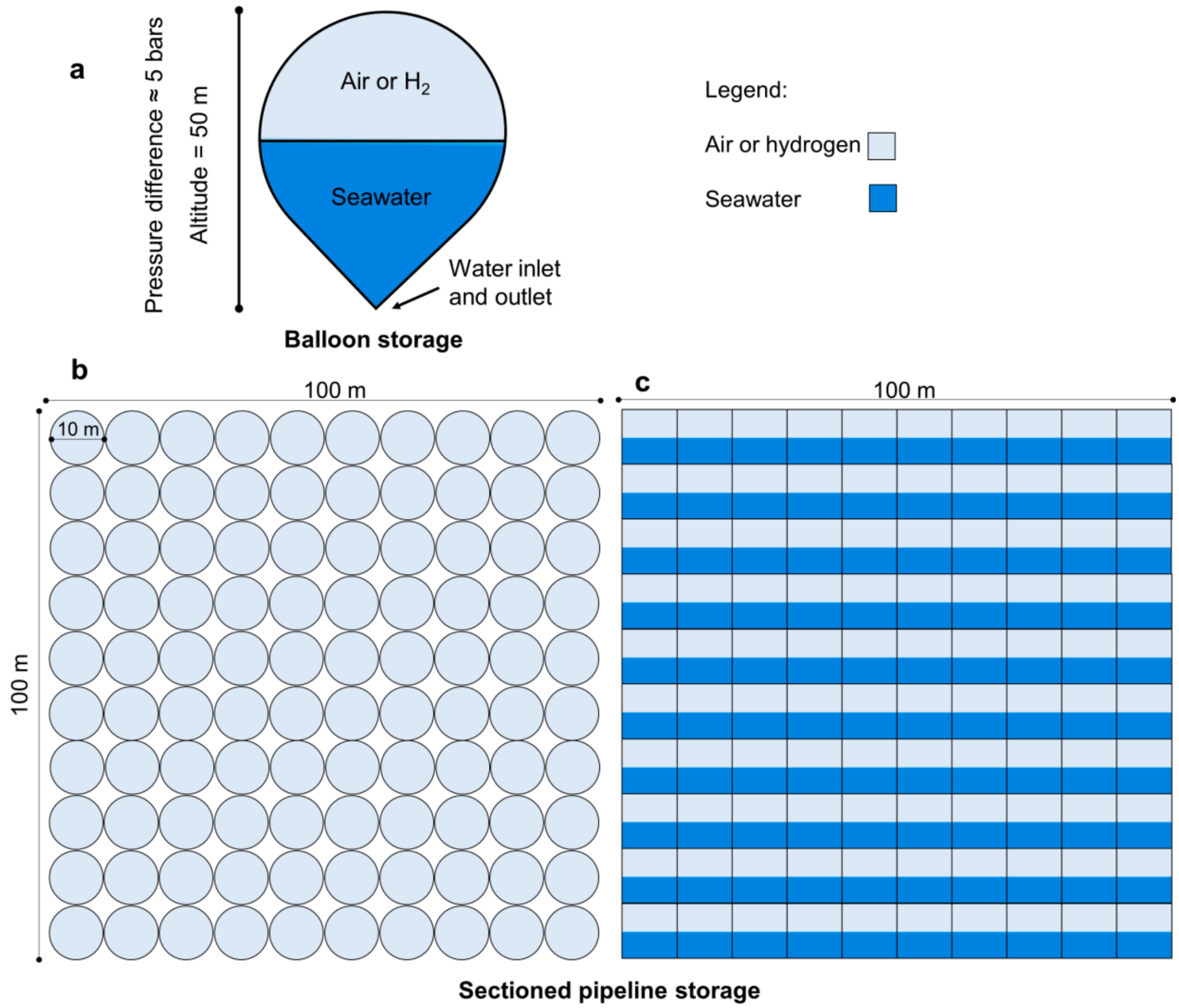


Fig. 3. (a) Balloon storage recipient and (b) vertical and (c) horizontal view of the sectioned pipeline storage recipient designs.

motor/generator can be built underwater and attached to the anchor platform and to a cable storage device. This arrangement would depend on the costs and efficiency of the motor/generator that would have to operate underwater and at extremely high pressures. If this alternative does no prove to be viable, then the cables could be connected to a ship floating on the surface. Note that the ship will only have to support a fraction of the total forces of the system, due to the pulley system; 4) An underwater transmission line system is required to connect the motor/generator to an offshore wind power plant or to the coast; 5) The anchor is also a key component of the system. It must sustain the very high buoyancy forces created by the storage recipient. To be able to support the system, a screw type (Helix) anchor could be implemented. The anchor would be made of steel and screwed to the bottom of the ocean with a system similar to an oil rig. Fig. 2 presents the representation of the anchor of a BEST system. The weight of the ground where the forces are applied should be larger than the buoyancy force of the recipient. The anchor platform houses the pulleys for the cable system, the motor/generator and the cable storage cylinder.

This system stores energy by consuming electricity in a motor that pulls the buoyancy recipient to the deep sea. It then generates electricity by slowly raising the buoyancy recipient supported by the generator. The rising and lowering speed must be low because of the losses due to friction, which are high under water. A speed of 0.01 m/s is estimated to minimize friction [28], which in 3.5 days of operation results in a depth of 3024 m. The system can increase or decrease the rising and lowering velocity of the buoyancy recipient according to the power requirements for the system. As the power costs of the system is high, the system should operate close to its maximum capacity. The niche for the operation of the system is to store energy in weekly cycles in synchrony with a battery system storing energy in daily cycles, or to compress hydrogen in an efficient way.

The design of the buoyancy storage recipient must consider the high underwater pressures. Two main designs are considered in this paper: the balloon storage design (Fig. 3(a)) and the sectioned pipeline storage design (Fig. 3(b) and (c)). In both designs, the amount of mass of compressed gas inside the storage recipients is constant. With the rise and fall of the storage recipient, the air expands or contracts, which results in the entrance or release of water from the storage recipient, respectively. A hole is required to allow the seawater to enter and leave the recipient. The balloon storage design is not a good design, because the pressure inside the balloon is constant and equal to the pressure on the compressed air/seawater layer. However, the pressure difference in the top of the balloon increases with the height of the compression gases in the balloon. For example, in a balloon with a height of 10 m, the pressure difference between the air inside and the balloon and outside is around 1 bar, which is too high for a plastic balloon and would cause it to collapse [59]. The sectioned pipeline storage solution is convenient, because the head of compressed gas is limited to 10 m, which is equivalent to 1 bar, and can be sustained with high-density polyethylene (HDPE) pipes. The hydrogen permeation and destruction potential under high pressure conditions for HDPE is small, particularly for HDPE (PE100) [60].

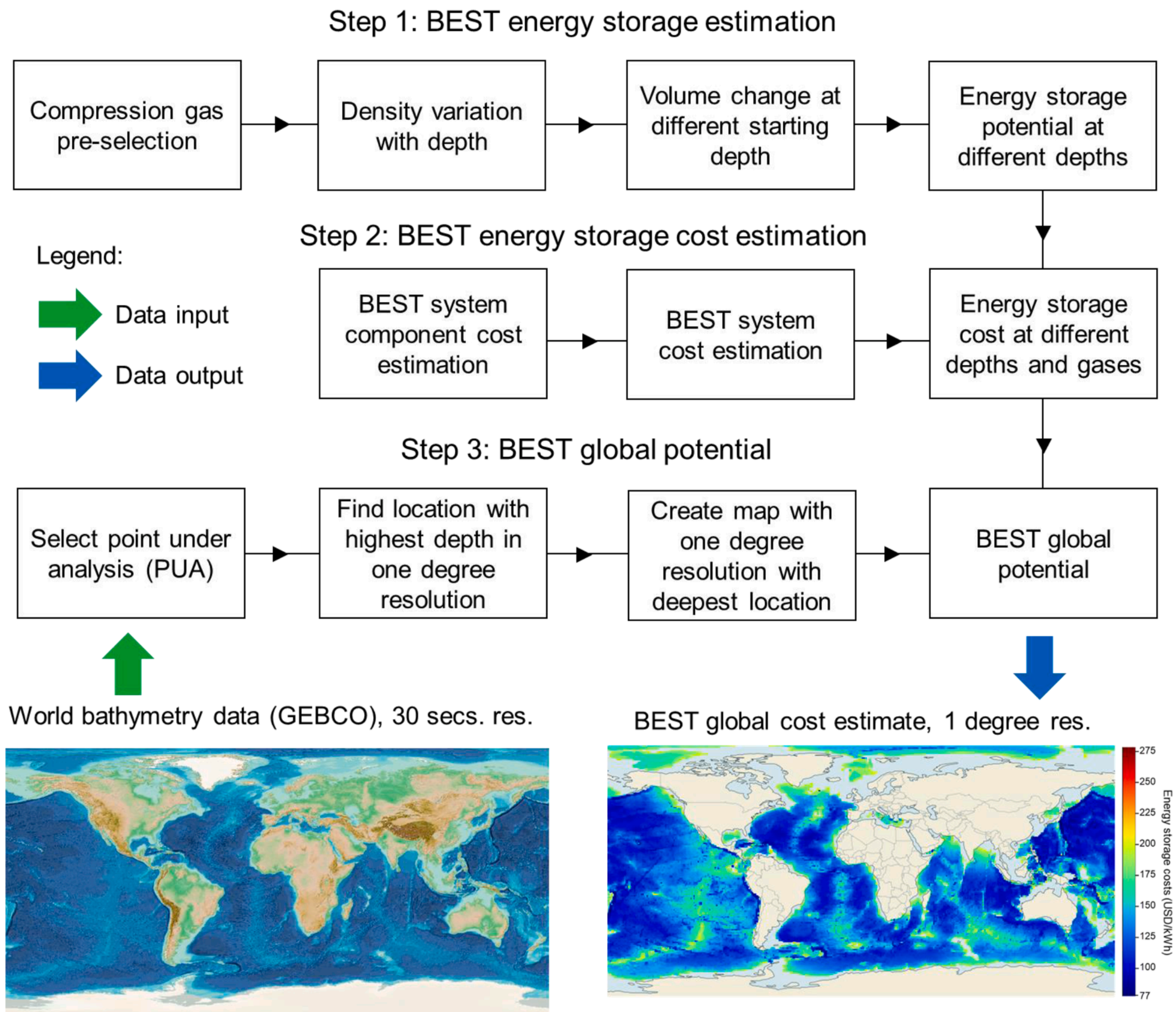


Fig. 4. Flow chart describing the methodology implemented in the paper.

Fig. 3(b) and (c) presents the proposed design for the storage recipient. Each pipe section functions individually, with water entering and leaving each of the sections, from lateral holes on the bottom of the sections, where both sides of the pipeline are always filled with seawater. As the recipient is lowered and the pressure increases, the gas is compressed, and water enters the recipient. When the recipient is moving upwards, the pressure difference between the inside and outside increases, pushing water out. The solubility of gases in water increases substantially with the increase in pressure. Given that the storage recipient will be filled with seawater every storage cycle, the amount of gas in the storage containers will be reduced in every storage cycle. Thus, a plastic envelope that is resistant to seawater and the compression gas should be used to impede that the compression gas enters into contact with the seawater. The envelope should have the same volume and shape as the pipeline section, where it is located. As the pressure inside and outside the envelope are similar, the envelope can be fin and made of plastic. Given the rapid reduction in volume of the compressed gas in the first 10 to 100 m from the surface, the installation of the system requires the support of a ship on the surface to lower the system to the minimum operation depth and then introduce the pressurized compressed gas to the system.

2. Methodology

The methodology implemented in the paper is presented in Fig. 4. It is divided in three main steps. Step 1 consists of estimating the energy storage potential of the proposed BEST system. It consists of the pre-selection of the compression gas used, the description of the density variation of the compression gasses with pressure, the change in volume of the compression gases at different starting depths and the estimate of the energy storage potential at different depth arrangements. Step 2 estimates the costs of the system components, BEST projects and the cost for energy storage with BEST. Step 3 produces a global potential for BEST with a resolution of 1° to highlight the hotspots for the technology.

Eq. (1) estimates the drag forces in the buoyancy recipient.

$$D = 0.5\, \rho_s\, u^2\, c_d\, A \qquad (1)$$

Where, D is the drag force, estimated to be 539 N. ρ_s is the density of sea water, which is around 1027 kg/m^3. u^2 is the velocity of the buoyancy recipient, assumed to be 0.01 m/s. c_d is the drag coefficient, it is assumed to be 1.05, as buoyancy recipient is shaped like a cube [61]. Note that the drag coefficient should be slightly smaller as the seawater can flow between the packed pipelines. A is the frontal area hit by the seawater and is the same for when the recipient is moving up or down. It shows that with an ascending and descending velocity of 0,01 m/s, the drag

Table 1
Description of the mass of the components in the BEST system.

Component	Buoyancy recipient	Cables
Density	0.95 g/cm^3 (It is convenient that the density of the material is lower than water, because it adds buoyancy to the system [65]).	7.80 g/cm^3
Volume	7.5 m^3/m (for each tunnel)	1854 m^3
Cable mass	–	1.75 kg/m [66]
Length	100 m (fixed length)	0 to 3 km (the length of the cables reduces with the depth of the system)
Quantity	100 pipes	2754 cables
Total mass	75,045 tons	14,459 tons (3 km long, discharged) 0 tons (0 km long, charged) 7229 tons (average)
Buoyancy share to support the BEST system	8.8%	1.8% (3 km long, discharged) 0% (0 km long, charged) 0.9% (average)

force account to only 0.00007% of the buoyancy force in a BEST system, thus it is not added to the energy storage potential equation. The reason why the system does not require a higher rising and descending speed is because the system is designed to store energy in weekly cycles. If the system had a higher speed, then it would only store energy for a few days. There are several technologies which can provide cheaper energy storage for daily cycles, such as chemical battery systems.

Eq. (1) estimates the power generation in the system and Eq. (2) expresses the energy storage capacity of the system.

$$P = v \times (V \times (\rho_s - \rho_c) - m) \times g \times e \times 10^{-6} \tag{1a}$$

Where, P is the power generated in the system, assumed to be 70 MW. v is the lowering or rising velocity in case of the generation and storage mode, respectively, which is assumed to be 0,01 m/s. V is the volume of compressed air in the buoyancy recipient, assumed to be a maximum of 785,000 m^3. ρ_c is the density of the compressed gases that vary significantly with the depth of the system and was taken from [62,63]. ρ_s is the density of the seawater, which is around 1027 kg/m^3 but which also varies with depth [64]. m is the mass of the BEST system, including the buoyancy recipient and the cables. The mass of the buoyancy recipient is equal to 75,045 tons. The mass of the cables in the BEST system varies from 14,459 tons, when the system is discharged (length of 3 km), to 0 tons, when the system is charged (length of 0 km). The average mass of the cables in the BEST system is 7229 tons. The more cables suspended by the buoyancy recipient, the higher the mass of the system. A description of the weigh on the system components is described in Table 1. g is the acceleration of gravity and equal to 9,81 m/s^2. e is the efficiency, which with a maximum speed of 0.01 m/s, the losses with drag are small, however, there are still losses in the motor/generator and from the friction in the pulleys, which accounts for 90% and an overall round-trip efficiency of 80% [28]. The isothermal compression of the gases in BEST systems follows Boyle's law, which contributes to the high efficiencies of the system.

$$E = \int_{d(\min)}^{d(max)} P \tag{2}$$

Where, E is the energy stored in the system. d is the depth of the buoyancy recipient that is assumed to vary from 3000 up to 10,000 m.

3. Results

3.1. BEST energy storage estimation

The selection of compression gas is important in BEST systems. This paper compares the use of air and hydrogen as compressed gases. Fig. 5 (a) presents the difference in density between the compressed gases at different depths. Air density increases substantially with depth, reaching

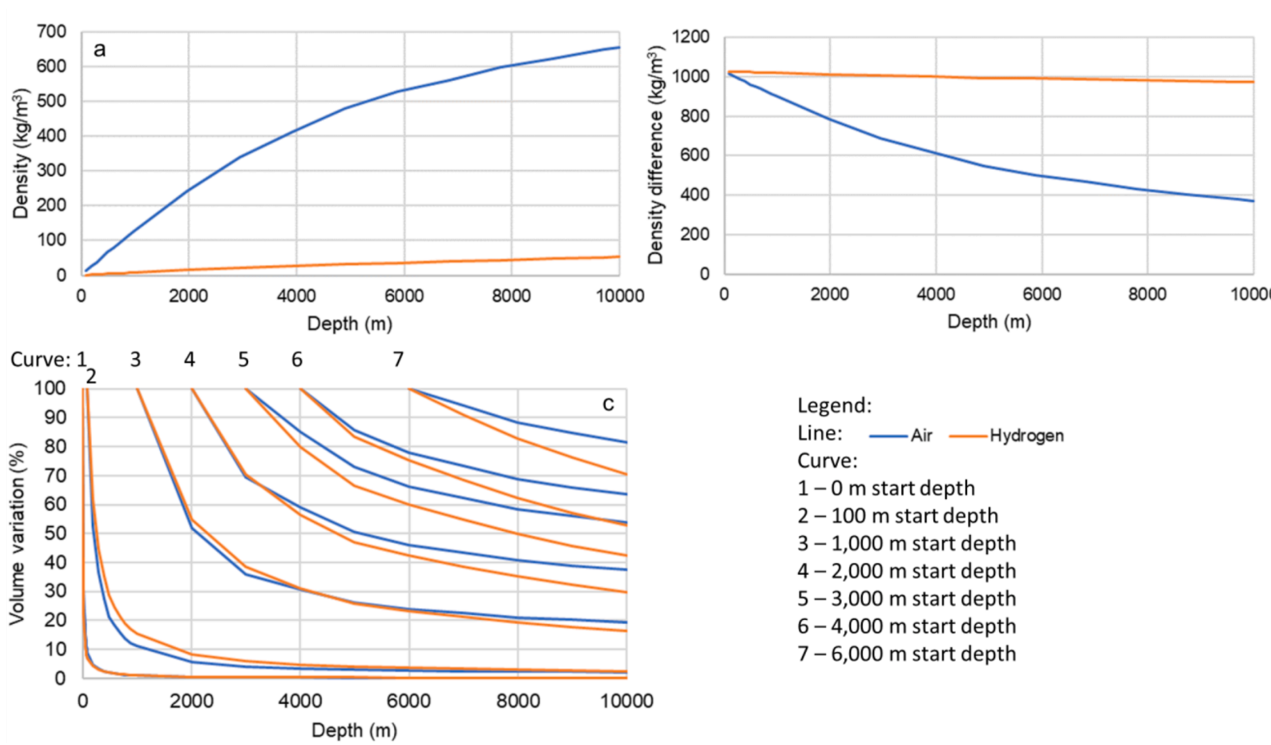
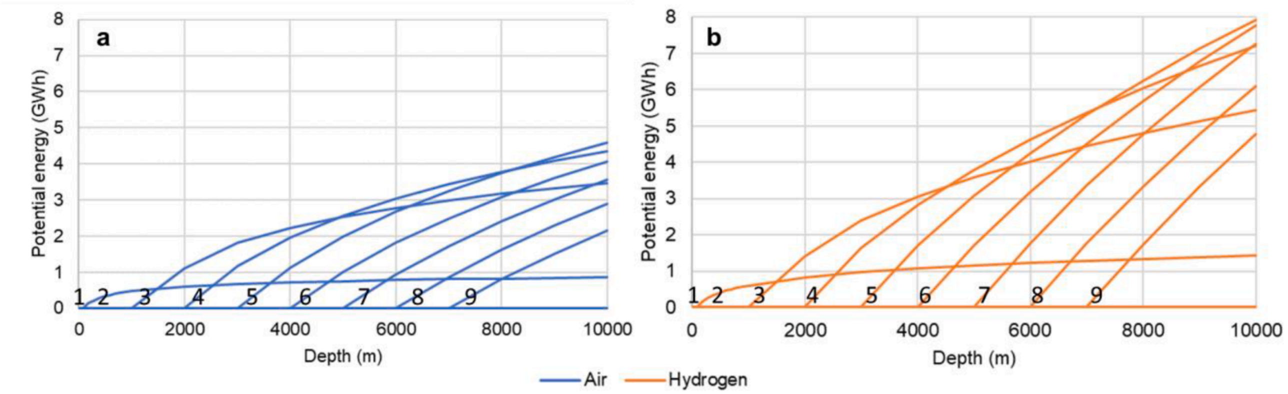


Fig. 5. Comparison between air and hydrogen compression gases, showing the change in (a) density, (b) buoyancy potential and (c) volume with both gases at different depths.



c

Details on the curves above can be seen below:

Curve number	Curve starting at depth below (m)	Air BEST system		Hydrogen BEST system	
		Energy storage with maximum depth of 6.000 m (GWh)	Energy storage with maximum depth of 10.000 m (GWh)	Energy storage with maximum depth of 6.000 m (GWh)	Energy storage with maximum depth of 10.000 m (GWh)
1	0	0.002471	0.00144	0.004808	0.003234
2	100	0.782785	0.859826	1.222469	1.439128
3	1000	2.786439	3.476624	4.028629	5.445249
4	2000	3.030163	4.362718	4.619819	7.203068
5	3000	2.670159	4.586633	4.247236	7.913782
6	4000	1.814802	4.06998	3.183681	7.766864
7	5000	0.932736	3.561657	1.762814	7.262634
8	6000	-	2.897532	-	6.0973
9	7000	-	2.147004	-	4.765873

Fig. 6. BEST energy potential (a) with air and (b) hydrogen compression gases, for a buoyancy recipient volume of 785,000 m^3, (c) description of the curves representing different BEST system arrangements at different depths.

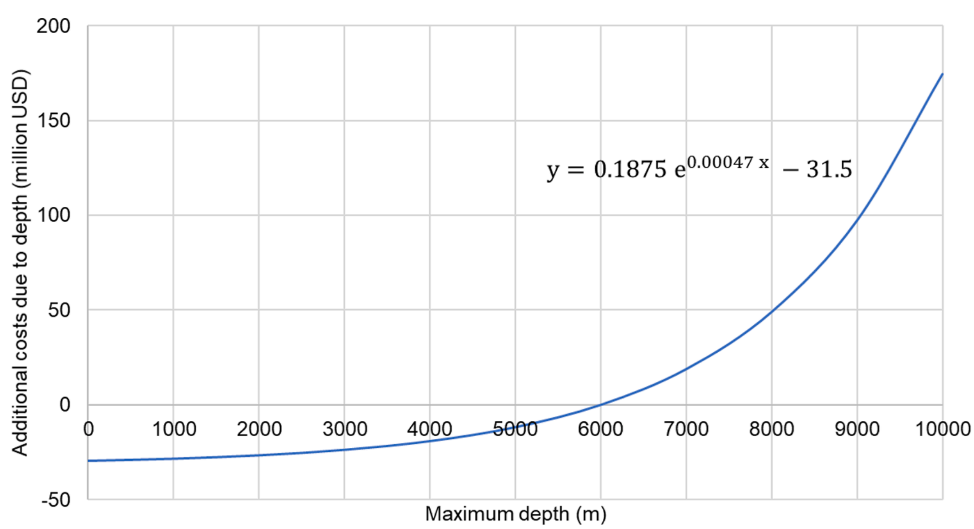


Fig. 7. Impact of depth in the construction costs of the system. This estimate was adapted from [71].

a density of 528 kg/m^3 at 6000 m, while hydrogen density remains small. High density is not ideal for BEST systems, because the density becomes similar to the density of the seawater 1028 kg/m^3, reducing the buoyancy potential (Fig. 5(b)), which impacts on the overall capacity of the system to store energy with a given storage volume. Another issue is that the volume of the gases reduces significantly due to the increase in pressure (Fig. 5(c)), which also reduces the energy storage potential of the system. Fig. 5(c) shows the variation in volume of the compression gasses with a BEST system starting at a given depth with 100% volume of compressed gas and the final relative volume of compressed gas in the recipient at higher depths

The change in potential energy at different ocean depths and pressures is presented with different BEST arrangements in Fig. 6. As it can be seen, the BEST system that can store the most energy is the one that starts at 1000 bars (maximum depth of around 10,000 m) and stops at 300 bars (minimum depth of around 3000) for both air and hydrogen as compressed gases. If the designed minimum pressure of the system is smaller, the volume of the gas it will reduce substantially, reducing the

Table 2
Cost estimate for BEST system components with 70 MW and 7914 MWh capacity.

Component	Cost description	Cost
Cables	3.5 km of cables, 285 KN, 8,3 USD/m each,, 2754 cables with 30 mm from [66] are required and results in a cost of 80, 000,000 USD. A larger cable could further reduce costs.	91,430,000 USD
Buoyancy recipient	100 HDPE pipes with 100 m. Extrapolating the costs in [65], it is estimated a cost of 120 USD per metre of pipe.	1200,000 USD
Anchor	The weight of the anchor is assumed to be 10% of the maximum buoyancy recipient force. The cost of steel is taken from [68]. The cost of steel assumed is 2000 USD/tonne.	157,000,000 USD
Motor/generator	Power capacity of 70 MW. Power costs 1000 USD/kW [69].	70,000,000 USD
Construction	50% of the equipment costs due to the complexity of the project.	159,815,000 USD
Hydrogen	Cost of hydrogen of 6 USD/kg [70].	4710,000 USD
Other	Other components which have negligible costs are the plastic envelope used to separate the seawater and compression gases, the pulley system, and the cable storage system.	–
Additional costs with depth	The additional costs with depth vary according to Fig. 7. The reference depth, i.e. the altitude in which the additional cost is zero is set to be 6000 m.	0
Total project cost	Total project cost assuming a depth of 6000 m	484,155,000 USD
Energy storage cost (USD/kWh)	Assuming the cost of all components and storage capacity 4.6198 GWh, that is at a maximum depth of 6000 m and a varying depth of 4000*.	105 USD/kWh
Power cost (USD/kW)	Assuming the costs of all components and storage capacity*.	6917 USD/kW

* There is not much flexibility in increasing only the energy storage capacity or power capacity because of the limitation of ascending and descending speed due to underwater drag.

energy storage potential of the system. If the designed minimum pressure increases, the altitude variation in which the system can operate reduces, reducing the energy storage potential. Thus, the results show that the ideal minimum pressure of the system to achieve the highest energy storage potential is 300 bars if the maximum pressure is 1000 bars.

Hydrogen advantage is that even though the density of hydrogen increases with depth, the difference between the compressed hydrogen and water at high depths is maintained at high levels. This allows the system to reach very high depths without losing the buoyancy capacity, and thus increasing the energy storage capacity of the system. The density at high pressures for air and hydrogen were taken from [62,63]. The oceanic pressure at different altitudes was taken from [64], and the equatorial latitude was used in the paper.

As a comparison, if a storage recipient with a volume of 785,000 m^3 were filled with water and descended by gravity to 10,000 m and generating electricity with an efficiency of 90%, the system would store 19.3 GWh of electricity [67]. This is similar to the storage capacity of the Ludington Pumped Storage Power Plant in the USA. The proposed BEST system with the same storage recipient volume and hydrogen as compressed gas, generating electricity from a depth of 10,000 m to 3000 m and an efficiency of 90% can store 7.9 GWh of electricity. On the other hand, if air were used in the system, it would store only 4.6 GWh. These and other operational arrangements are presented in Fig. 6c.

3.2. BEST energy storage cost estimation

The main challenge to implementing this system is the costs of the cables and the anchor, to support the buoyancy recipient. Table 2 presents a cost estimate for an arrangement that operates from 300 bars to 1000 bars with hydrogen. Fig. 8 presents the BEST energy storage costs in USD/kWh for air and hydrogen with different available depths. These costs can be significantly reduced if substantial investment is made in the technology.

3.3. BEST global potential

A model has been created to assess the global potential for BEST with hydrogen and air as compressed gases. This consists of an analysis of the world bathymetry with a 30 arc-seconds resolution (900 m at the equator and smaller with the increase or reduction in latitude), with the data obtained from GEBCO [72]. The world potential consists of the

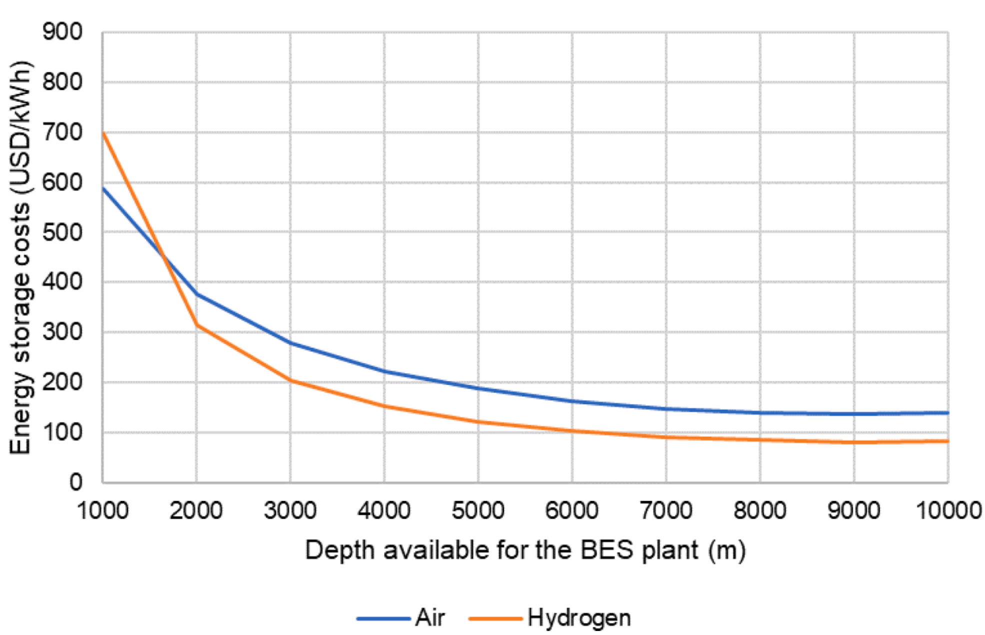


Fig. 8. BEST energy storage costs in USD/kWh for air and hydrogen with different available depths.

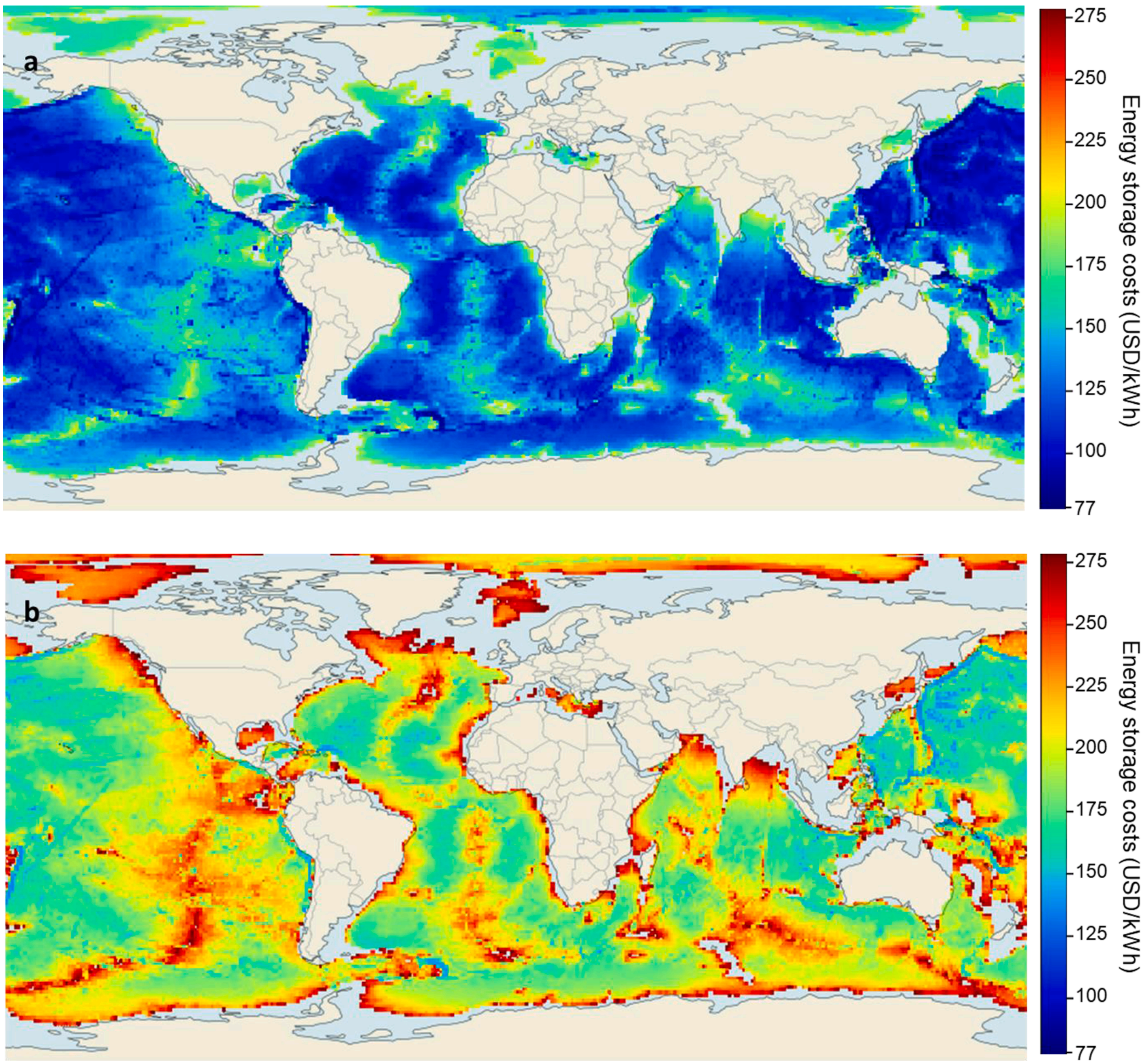


Fig. 9. World potential of BEST with (a) air and (b) hydrogen as the storage medium. The greater the depth, the higher the BEST potential.

energy storage potential at a certain depth of the ocean using hydrogen and air. The depth presented in the paper started from 3000 m to better presents the locations with higher potential. The world potential for BEST is presented in Fig. 9(a) for hydrogen and Fig. 9(b) for air. The relation between the storage cost and the depth is presented in Fig. 8. Each degree of resolution in Fig. 9 represents the 30 arc-second resolution location with the greatest depth, in order to better present the results. As it can be seen, the locations with the highest potential are oceanic islands and on the coasts of Japan, Philippines, Indonesia, Australia, USA, Mexico, Chile, Peru, Ecuador, Colombia, Cuba, Jamaica, Guatemala, Honduras, Brazil, Portugal, Oman, South Africa, Madagascar and Somalia, Ivory Coast and Ghana.

3.4. Assessment of global potential of BEST

With the intent of reproducing the operational scenario of a BEST plant, we proposed the construction of a floating offshore wind power project with 10 GW of installed capacity near Tokyo, Japan and used a BEST and battery systems with an installed capacity of 7 GW and a storage capacity of 300 GWh to reduce the wind generation fluctuations. Given the low hourly and daily storage cycles in the wind generation, batteries were not included to operate in synchrony with the BEST system. The hourly offshore wind generation profile uses data from the Renewable Ninja site [73] at the coordinates of 34.6761 latitude and 141.8244 longitude in 2019, for more details on the methodology for the wind power time series see [74]. The desired demand output consists of the average wind power generation of one week ahead and prior to the hour under analysis. This is presented in Fig. 10(a). Fig. 10(b) presents the energy storage contained in the BEST plans in GWh. As it can be seen, the BEST plant operation focuses on storing energy mainly in weekly cycles and occasionally in hourly and daily cycles, as it is designed to operate. This is convenient, because the installed capacity of BEST (GW) is high, however, the costs for energy storage are low (GWh). Note in Fig. 10(a) that there are losses in the energy storage system because the energy storage system does not have the capacity that is required to store all excess offshore wind generation and sometimes the battery does not have enough charge to meet the desired demand. These offshore wind power curtailed are equivalent to 4% of the total offshore wind power generation. The capacity factor of the BEST system is 20.3%.

4. Discussion

BEST is located far from the conventional demands for electricity,

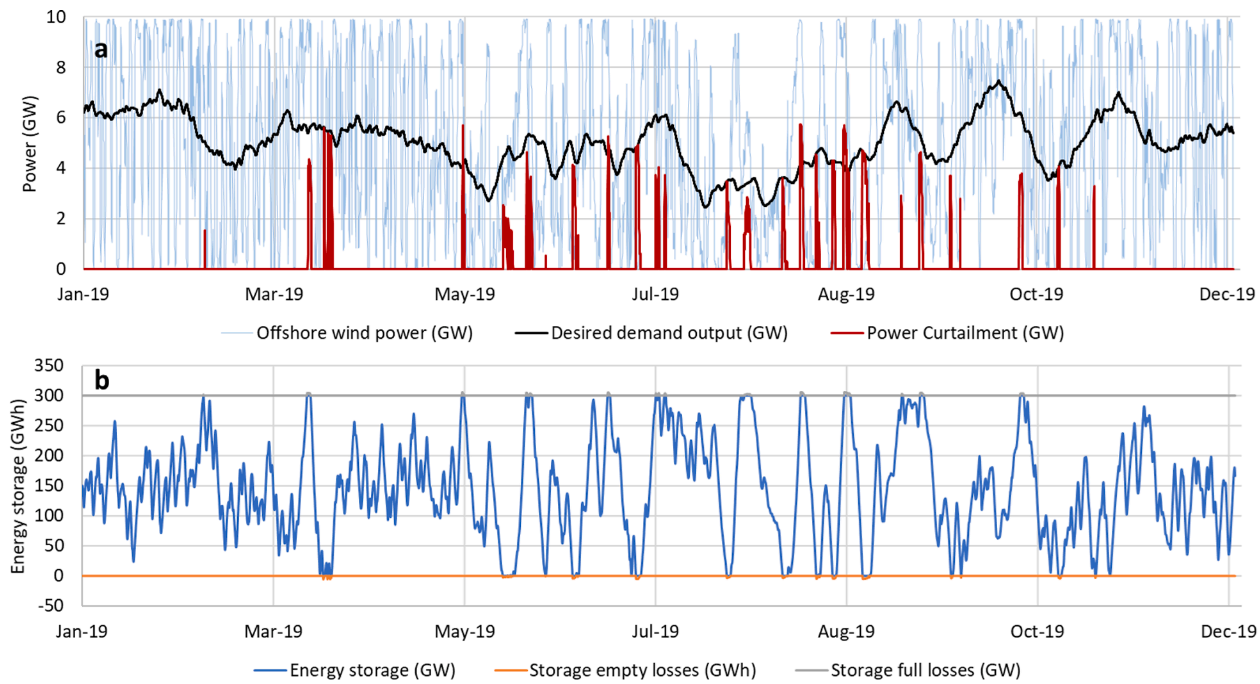


Fig. 10. Proposed operational scenario for BEST to store offshore wind power near Tokyo, Japan. (a) wind power, electricity demand and energy losses (GW), (b) energy storage (GWh).

Table 3
Viable scenarios for implementing BEST systems.

Scenarios	Description
Coastal areas	Coastal areas without mountains suitable for pumped storage could be a possible alternative to BEST systems. However, some coastal areas have long continental plates, which would increase the cost of the project due to the increase in underwater transmission costs.
Islands	Islands usually have a short continental plate, which allows a BEST system to be installed a few kilometres from the island.
Offshore wind power close to the coast	BEST could be used to store wind energy, particularly because it can operate in weekly storage cycles, which is convenient for reducing the intermittency of wind power plants.
Floating offshore wind power for hydrogen generation	For floating offshore wind power, the potential of BEST is vast due to the great depths available in the world's oceans, far from the coast.
Hydrogen compression	Current technology for compressing hydrogen to 600 bars usually has an efficiency of around 40 to 50%. BEST systems can compress hydrogen with efficiencies around 90%.
Deep sea mining	Deep sea mining will demand a lot of electricity in the future, which could be met with offshore wind power and fuels, such as hydrogen. BEST can support offshore wind power plants to guarantee the supply of electricity during weeks with low wind power generation.

Table 4
Comparison of BEST costs with other technologies (cost data from [10,14,77]).

	Cost of installed capacity (M USD/MW)	Cost of energy storage (USD/MWh)	Capacity (MW)
Pumped-storage	0.4 - 1	5 - 50	100 - 2000
Batteries (Li-ion)	0.25	200	1 - 500
BEST	4 - 8	50 - 100	10 - 100

thus it is a solution limited to some locations and applications. Table 3 presents the scenarios is which BEST could be viable.

Given the high power (MW) and low energy (MWh) storage costs, BEST plants would be designed to store or generate a constant amount of energy in weekly cycles, particularly to store wind power generation. It could be combined with other storage technologies, such as batteries, to balance hourly and daily energy storage cycles. Table 4 presents the main characteristics of BEST compared with other mechanical and electrochemical energy storage systems. The lifetime of BEST systems is assumed to be 15 years, with some equipment having to be replaced before the end of the lifetime, due to the marine environment corrosion, such as the cable system. Assuming a capacity factor of 20%, discount factor of 3%, free electricity cost for storage, and O&M costs of 5% of capital costs, the levelized cost of a BEST system with maximum depth of 6000 m and depth variation of 4000 m is 49.6 cents/kWh [75]. Note that this cost can reduce significantly with investment in the technology to lower component and construction costs. A comparison with other energy storage technologies can be seen in [76].

Compared with pumped-storage and batteries, BEST systems have a substantially lower environmental footprint. It does not require to flood an area to create a reservoir and it does not require a large volume of mined resources. The environmental impact of BESS systems is limited to the anchor platform on the bottom of the ocean, the cables and the rise and fall of the buoyancy recipient. The impact of the buoyancy recipient is small due to its low ascending and descending speeds. The cables, however, have a larger speed due to the pulley system, and animals that rest on the cable might suffer from rapid changes in depth or end up being crushed by the pulley system. Mitigation measures should be applied to minimize as much as possible this potential impact. For example, the cable system could be protected by pipes or a plastic, to avoid the aquatic fauna to reach the cables.

There are some risks related to the system, if the anchor or cables are not carefully designed and fail to support the storage recipient, it will rise rapidly and damage any infrastructure above the BEST system. The damage to infrastructure would be more significant, particularly, during construction or start-up, when there are vessels on the surface. An alternative to reduce this risk is to design the pipelines to detach from each other if they suffer large forces for the rapid rise resulted from the

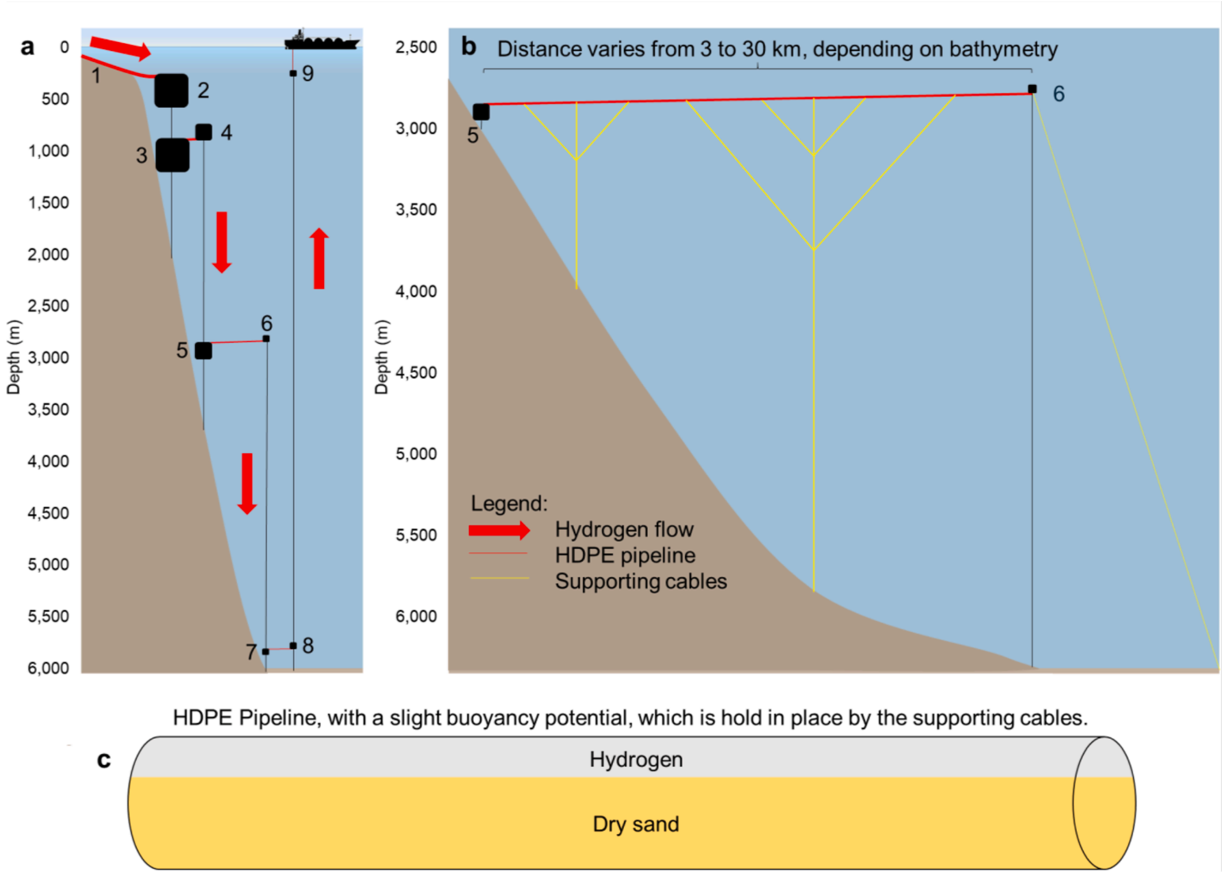


Fig. 11. BEST hydrogen compression system. (a) System divided into tree stages,.

failure. This would reduce the potential for destruction of the system.

4.1. Hydrogen compression with BEST

The advantage of compressing hydrogen with BEST is the higher energy efficiency of the system. The compression of hydrogen to reach pressures of 600 bars usually has an efficiency of around 40%. On the other hand, the efficiency of hydrogen compression with BEST systems could be as high as 90%. However, if the BEST system were used to compress hydrogen, the system would not be used as an energy storage device. It would be a hydrogen compression device. This is because once the buoyancy recipient reaches the deep sea, the compressed hydrogen is contained in a pressure vessel at 600 bars and submerged to the surface. The buoyancy potential of the recipient will be just enough for the recipient to float back to the surface. However, the system can still be used as a demand side management solution for consuming excess electricity, with high response time.

Given the large variation in volume in BEST systems with the compression of the hydrogen from 10 bar to 600 bar, a BEST hydrogen compression (BESHC) system should be divided into two or more sections to optimize the system. Fig. 11 shows a system with three sections where: 1) corresponds to a hydrogen pipeline from the coast to the first section of the BESHC; 2) is the first section of the BESHC being charged with H_2 from the coast; 3) is the first section of the BESHC being discharged to the second section of the BESHC; 4) is the second section of the BESHC being charged by the first section of the BESHC; 5) is the second section of the BESHC being discharged to the third section of the BESHC; 6) is the third section of the BESHC being charged by the second section of the BESHC; 7) is the thirds section of the BESHC being discharged to the forth section of the BESHC; 8) is the four section of the BESHC being charged by the third section of the BESHC; 9) is the forth section of the BESHC being discharged to the storage cargo ship.

Fig. 11(b) presents a proposal for transporting the hydrogen from a state to another. This will be performed with a floating pipeline filled with hydrogen and sand (as shown in Fig. 11(c)). The hydrogen increases the floating potential of the pipeline and the sand increases the weight of the pipeline. Thus, the pipeline remains in place with a slight buoyancy potential, which is held in place by the supporting cables attached to the ground. Most of the volume in the pipeline should be filled with sand because the space between the sand particles will be filled with hydrogen, which will contribute to increase the buoyancy of the pipeline. The pipeline should be slightly inclined so that the hydrogen flows naturally to the other stage, without the aid of pumps. To increase the viability of the system the pipeline should be used as much as possible. Thus, there should be several BESHC systems working in parallel to continuously supply hydrogen to the pipeline and to the other stage.

Assuming the cost of BESHC is five times higher than BEST, due to the lower average depth and the requirement of the hydrogen pipelines between different stages, the costs for compressing hydrogen is around 2617 USD/(m^3/d). The cost of compressing gas with conventional technologies is estimated at 85,948 USD/(m^3/d) [78], a value 33 times higher than BESHC systems.

4.2. Demand for energy for deep sea mining

The increase in deep sea mining will require an increase in electricity demand in the middle of the ocean [79]. BEST could be an alternative for improving the quality of the supply of electricity demanded by the equipment underwater. The underwater machinery applied in deep sea mining applications operate 100% on electricity, as other fuels are not an alternative due to the lack of oxygen at the bottom of the ocean. The

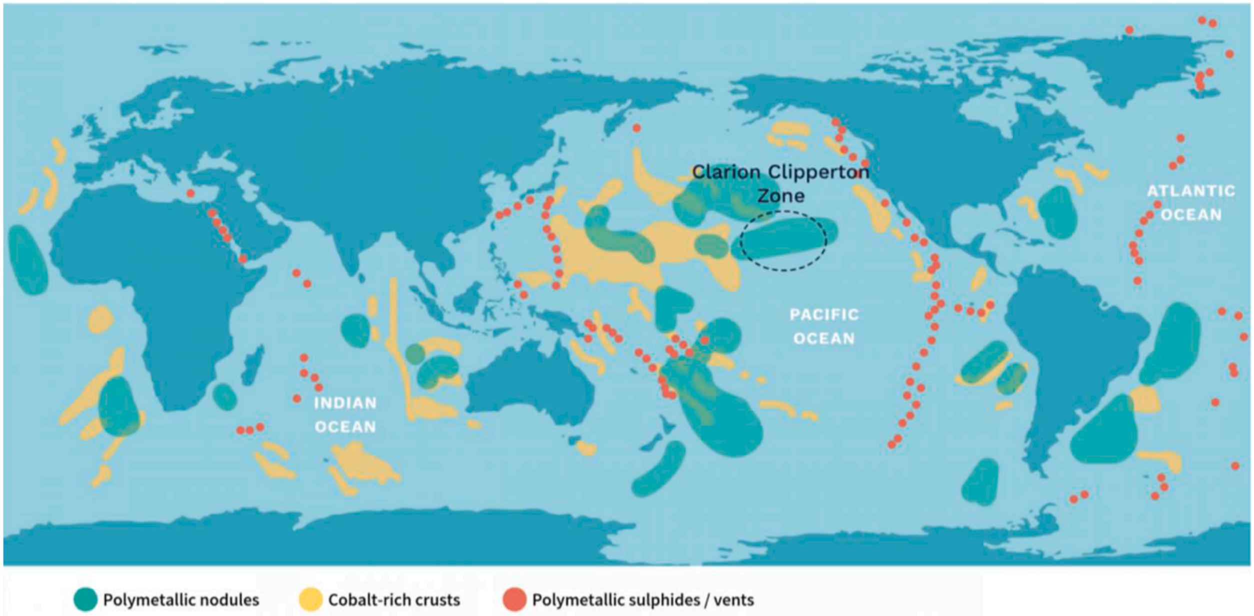


Fig. 12. Global potential for deep sea mining: polymetallic nodules, cobalt-rich crusts, sulfide deep sea mining [81].

deep sea mining operation that is most suitable for BEST is that for polymetallic nodules, which are usually located at depths between 4000 and 6000 m [80]. These polymetallic nodules are rich in manganese, nickel, copper, cobalt and other rare earth metals, which are important components in the production of lithium-ion batteries and other sustainable energy technologies. BEST can also be used as an alternative for carrying the minerals extracted from the deep sea to the surface. Fig. 12 presents a map with the world potential for deep sea mining.

Conclusions

This paper proposes a novel energy storage solution to fill the gap between existing short-term and long-term storage options. The proposed Buoyancy Energy Storage Technology (BEST) solution offers three main energy storage services. Firstly, BEST provisions weekly energy storage with low costs (50 to 100 USD/MWh), which is particularly interesting for storing offshore wind energy. Secondly, BEST can be used to increase the efficiency of hydrogen compression up to 90%. Thirdly, BEST can offer spinning reserve services for power balancing and frequency control with a millisecond response time.

The system moves at a maximum speed of 0.01 m/s. With a 3.5 km depth (7 km return), results in a cycle of 8 days. Each system can only cycle 40 times per year. This type of energy storage cycle is interesting, particularly to store wind power, which usually have weekly cycles.

Given that the capital cost of batteries has been reducing significantly in the last several years, the BEST system is designed to be possibly paired with batteries, to complement batteries as a low-cost electricity storage option (USD/MW). Thus, the combination of both systems will offer an energy storage solution with low cost of stored energy (USD/MWh) and low cost of power capacity (USD/MW). BEST system operates slowly, but constantly charge and discharge in a weekly cycle, while the battery will rapidly charge and discharge in a 6 to 24 h cycle. This hybrid operational strategy guarantees that the BEST system will receive electricity to operate at its highest capacity factor, as the cost of the technology (USD/MW) is relatively high.

The cost of BEST varies between 4 and 8 million USD/MW of installed capacity, and 50–100USD /MWh of energy storage cost, with projects varying in sizes of 10 to 100 MW. The greater the depth of the ocean, the lower the cost of the project, and hydrogen has proven to be a better storage media compared to air as a compressed gas.

Most areas with depths suitable to low-cost BEST are not well suited to offshore wind, as the costs to anchor offshore wind turbines with depths above 1000 m are still prohibitive. The locations with the highest potential for BEST systems are oceanic islands and on the coasts of Japan, Philippines, Indonesia, Australia, USA, Mexico, Chile, Peru, Ecuador, Colombia, Cuba, Jamaica, Guatemala, Honduras, Brazil, Portugal, Oman, South Africa, Madagascar and Somalia, Ivory Coast and Ghana.

BEST is a competitive energy storage alternative that has not received much attention. Due to the increased interest in weekly energy storage and the need for efficient solutions for compressing hydrogen, it has the potential to become an important technology in the future energy storage market.

Author contributions

Conceptualization, J.H.; methodology, B.Z.; formal analysis, P.S.; investigation, W.L.; data curation, A.M.; writing—original draft preparation, J.H.; writing—review and editing, B.Z.; visualization, A.B.; project administration, P.S.; funding acquisition, A.M; resources, C.E; software, A.B;. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

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

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