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Hydrogen Deep Ocean Link: a global sustainable interconnected energy grid

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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, which is increasing the challenges to operate the power grid reliably. An option that has been receiving much focus after the COVID pandemic is the development of a hydrogen economy. Challenges for a hydrogen economy are the high investment costs involved in compression, storage, and long-distance transportation. This paper analyses an innovative proposal for the creation of hydrogen ocean links. It intends to fill existing gaps in the creation of a hydrogen economy with the increase in flexibility and viability for hydrogen production, consumption, compression, storage, and transportation. The main concept behind the proposals presented in this paper consists of using the fact that the pressure in the deep sea is very high, which allows a thin and cheap HDPE tank to store and transport large amounts of pressurized hydrogen in the deep sea. This is performed by replacing seawater with pressurized hydrogen and maintaining the pressure in the pipes similar to the outside pressure. Hydrogen Deep Ocean Link has the potential of increasing the interconnectivity of different regional energy grids into a global sustainable interconnected energy system.
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1. Introduction

The ever-decreasing cost of variable renewable sources (VRE) such as wind and solar PV has paved the way for large-scale penetration of such technologies [1–8]. Yet, for achieving climate targets such as "net zero", various solutions must be deployed, including hydrogen [9]. The hydrogen economy has received much attention after the COVID pandemic [10], as a solution to reduce the reliance on fossil fuels and the associated risks [11–13]. In many post-pandemic recovery programs, such as the EU Hydrogen Strategy, there is an emphasis on renewable hydrogen and ambitious plans to expand the hydrogen infrastructure to meet energy and climate targets [14,15].

One of the challenges for expanding the hydrogen economy is the transmission and distribution (T&D) and storage of hydrogen, especially in countries without an existing natural gas grid [16–18]. There are several solutions proposed for long-term and seasonal hydrogen storage [19–22]. These solutions are mainly based on storing hydrogen in underground caverns [23], depleted reservoirs and salt mines [24]. These solutions are mainly site-specific, limited by geological and accessibility limitations [25]. Other alternatives for storing energy seasonally are seasonal pumped hydropower storage [26–32], gravity energy storage [33], biomass [34], power to fuels [35,36] and thermal energy storage [37].

Hydrogen long-distance transportation has received a lot of attention in the literature. So far, the most discussed alternatives for transporting hydrogen to long distances are through pipelines, and a few solutions based on liquefaction and shipping [38]. Hydrogen could be mixed with natural gas and transferred and stored in the natural gas grid [39]. This is convenient as it transports hydrogen in a gaseous state without the need and complexity of liquefication and regasification [40]. However, pipelines could be an issue, as such infrastructure is not available everywhere and maybe a risky solution, particularly in conflict zones. Hydrogen can be

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transported with an intermediate energy carrier such as ammonia, methylcyclohexane, methanol and other [41–43]. The main issue with this alternative is the low energy density of the fuels and the challenges of producing the fuels and transforming them back to hydrogen. Hydrogen can also be transported in a gaseous state with airships or balloons [44]. As hydrogen is lighter than air, the airship or balloon would be designed to float on the stratosphere, and the wind would blow the hydrogen to its destination [45]. The route would be controlled by changing the altitude of the airship or balloon. Another recent proposal, suggests the transport of pressurized hydrogen with deep ocean H_2 pipelines [46]. The advantage of this proposal is that given the pressure inside and outside the pipeline are the same, the pipeline can be cheap. This paper further develops this concept.

There are also several solutions for highly efficient, isothermal hydrogen compression. The AirBattery is an innovative compressed air storage (CAES) solution that stores air isothermally with the displacement of air with water, at high efficiencies [47]. The water pressure is increased with the aid of pumps. The electricity is then generated by using compressed air to push water in a hydropower turbine to generate electricity. A similar system could be implemented to compress and store H_2 cheaply and efficiently. This paper proposes a similar solution for hydrogen compression named deep ocean H_2 isothermal compression, however, instead of using turbines to increase the pressure, the pressure is increased by increasing the depth of the storage tank in the sea and allowing seawater to enter the tank and compress the H_2. The advantage of the proposed technology is that the storage tanks are made of cheap HDEP pipes, while the AirBattery is made of expensive pressure tanks. The disadvantage of the proposed technology is that it is limited to the deep ocean. The main contributions of this paper to the literature are to propose the use of the deep ocean of hydrogen compression, log-term storage, and transportation. The use the deep sea high pressure for hydrogen compression, log-term storage and transportation has not yet been proposed in the literature [48–53]. The paper investigates the costs of the technology. Furthermore, by applying a GIS-based analysis, this study investigates the global potential of HYDOL, which provides the first-of-its-kind assessment of the potential contribution of such storage technology. The proposed designs in this paper have been developed by the authors and are considerably different from what has been proposed in the literature.

2. Methodology

The methodology implemented in the paper is presented in Fig. 1. It is divided into three main steps. Step 1 “HYDOL weight balance at different depths”. This step is divided into four sub-steps the “Solubility of H_2 in water at different pressures”, “Density variation of H_2 seawater and sand with depth”, “Volume change at different starting depth”, “Weight balance of H_2 and seawater at different depth”. Step 2 “HYDOL proposed arrangements”. This step is divided into four sub-steps the “Deep ocean H_2 isothermal compression”, “Deep ocean H_2 long term storage”, “Deep ocean H_2 pipeline”, “Deep ocean H_2 submarine”. Step 3 “HYDOL global potential”. This step is divided into four sub-steps “Selection point under analysis (PUA)”, “Find locations with depth equal to 1 or 5 thousand”, “Locate deep ocean minimum depth bottlenecks”, “HYDROL global potential”.

2.1. HYDOL proposed arrangements

The main concept behind the HYDOL proposed arrangements is presented in Fig. 2 and consists of using the fact that the pressure in the deep sea is very high, which allows a thin and cheap HDPE tank to store large amounts of hydrogen seasonally or pluri-annually in the deep sea. This is performed by replacing seawater with pressurized hydrogen when filling up the tank and replacing the hydrogen with seawater when emptying the tank.

2.1.1. Deep ocean H_2 isothermal compression

The proposed deep ocean H_2 isothermal compression in this paper is shown in Fig. 3. The connection between the continent and the electrolysis ship is done with an underwater transmission line (Fig. 3 (a)) [54]. The electrolysis ship uses the electricity to desalinate seawater and produce H_2. The H_2 is pressurized adiabatically to a pressure of 100 bar. The pressurized H_2 is transported via a pressure pipeline to the isothermal compression device. The isothermal compression devise consists of 21 HDPE pipes filled with high porosity sand (where 60% solid and 40% liquid or gas) wrapped by cables connected to the electrolysis ship (Fig. 3 (b)). The pressurized H_2 (100 bar) replaces the seawater. Once the device is filled with hydrogen, it starts to descend as the system weight is higher than the buoyancy forces. The hydrogen and seawater balance to result in a smooth descent is detailed in the Results section. As the H_2 replaces the seawater in the outer pipes, the hydrogen is directed to the adjacent pipes increasing the H_2 pressure of all pipes and maintaining the pressure inside the pipes the same as the outside pressure. Once one outer pipe is filled with water and another is about to be filled with water, the first is detached from the cluster of pipes. This is important because if the pipe filled with sand and seawater reached the bottom of the ocean, the energy required to pull the pipes back to 1000 m would require significantly more energy. The proposal in (Fig. 3 (b)) has a compression efficiency of 90 to 80% efficiency. Once the 5 pipes with pressurized hydrogen at 500 bar and 5000 m depth, the hydrogen is stored in deep ocean H_2 long-term storage, pipeline, or submarine, and the 5 pipes are filled with seawater. After the H_2 is delivered, the ship powers a motor to pull the pipes filled with water back to an altitude of 1000 m, and the cycle restarts.

2.1.2. Deep ocean H_2 long-term storage

An interesting alternative to store hydrogen long-term cheaply is to use an HDPE tank filled with high porosity sand, as shown in Fig. 4. The tank is still in the deep ocean bed and always operates with the same pressure, which can vary from 50 to 600 bar, depending on the depth where it is located. The tank is filled with sand to maintain it on the seabed when it is filled with H_2. To discharge the H_2 stored, seawater is allowed to flow into the bottom of the tank, and the H_2 leaves the tank from the top. On the other hand, when the tank is being filled with H_2 from the top, seawater is removed from the bottom of the tank. The sand in the deep ocean H_2 long-term storage should have high porosity (60%) so that more H_2 can be stored in the sand. We propose that this solution should be used for long-term energy storage, because it is not practical to store H_2 on the deep ocean, however, the costs for storage are low.

2.1.3. Deep ocean H_2 pipeline

The deep ocean pipeline is designed to transport a large amount of hydrogen mainly between continents (Fig. 5 (a)), however, as the price of the pipeline is significantly lower than superficial pipelines, it can also the used to transport hydrogen within the coast of the same continent. The added benefit is that the pipeline can store large amounts of hydrogen even if it is not used to transport hydrogen. The pipeline consists of two pipelines, one inside the other, as shown in Fig. 5 (c). The outer pipe is filled with sand, hydrogen, and seawater, and the inner pipe is filled only has hydrogen inside. The weight and buoyancy balance of the pipeline is controlled by adding or removing hydrogen from the outer pipeline, as shown in Fig. 5 (c). For the hydrogen to flow in the

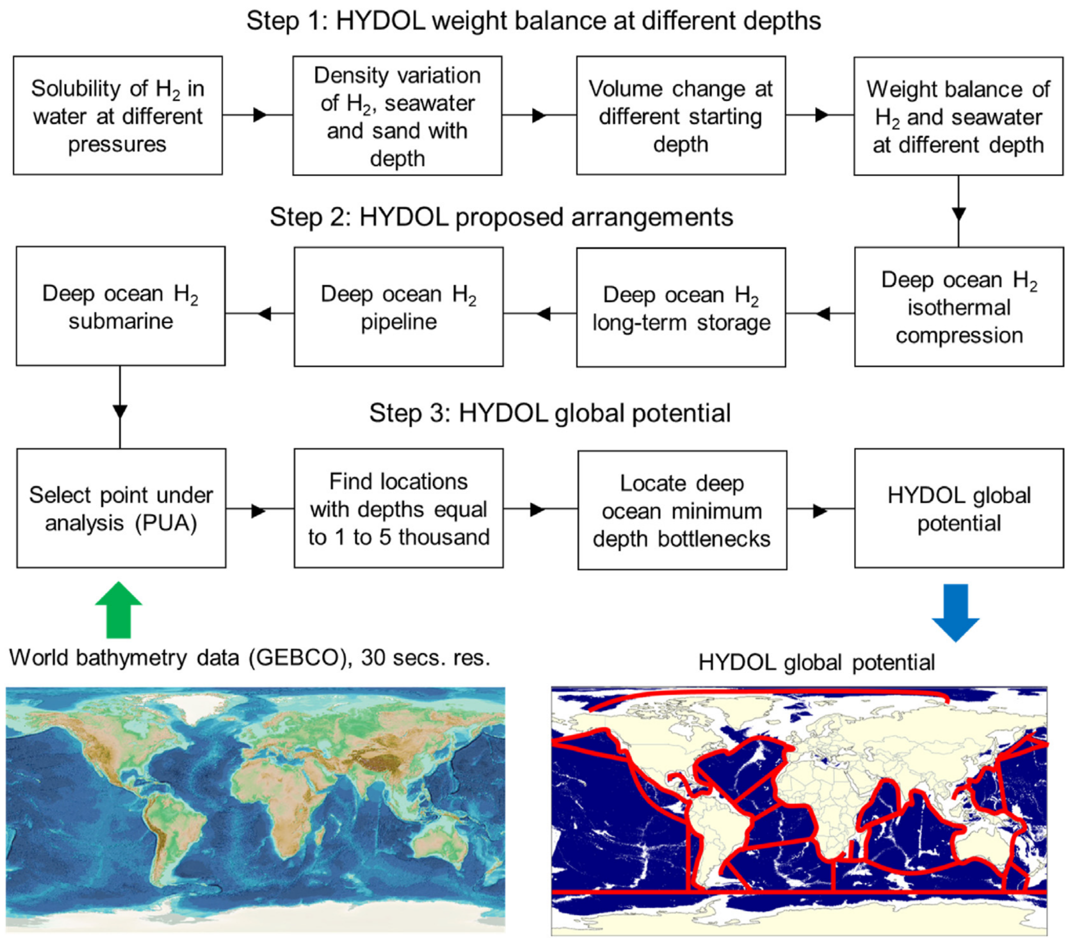

Fig. 1. Flow chart describing the methodology implemented in the paper.

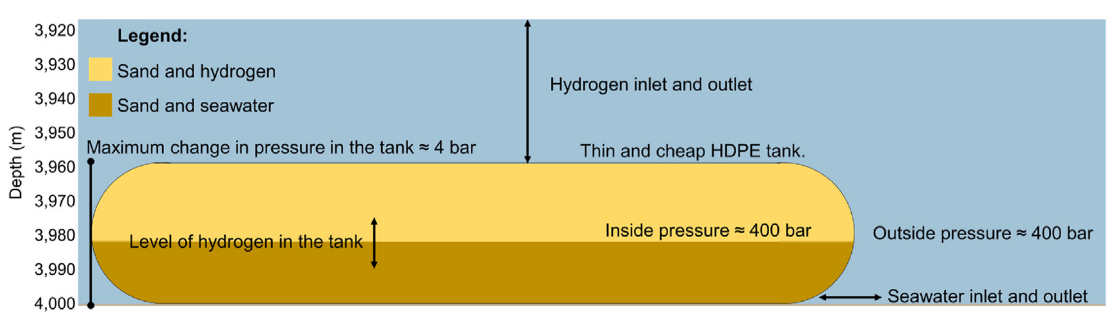

Fig. 2. Main concept behind the HYDOL solutions.

pipeline, the hydrogen pressure in the inlet much be higher than the pressure in the outlet. As the pressure inside and outside along the pipeline should be the same, the pipeline has to create a slope for both requirements to be fulfilled, as shown in Fig. 5 (b). The higher the slope, the faster the hydrogen will flow inside the pipes, and the higher will be the pressure difference between the pipeline inlet and outlet. The pipeline will not bend in a straight line, as shown in (Fig. 5 (b)), it will bend similarly to an exponential curve. This is because, as the pressure lowers the velocity of the hydrogen increases and increases the pressure drop in the pipeline. When the pressure in the inlet increases, some of the hydrogen flows to the outer pipeline displacing the seawater and increasing the depth of the pipeline. On the outlet, the pressure reduces, and water enters the outer pipeline, and more hydrogen enters the inner pipeline. The outer pipeline requires a separation layer every 5–10 km, to avoid hydrogen building up in the outlet side of the pipeline. The cables arrangement to control the depth of the pipeline has two fixed anchors and one moving weight to allow the pipeline to move according to its inner pressure and to the deep ocean currents (Fig. 5 (d)). Pipeline sections close to the cable connections have a higher floatability to increase pipeline positioning control. The pipeline section far from the cable connections has a weight and buoyancy equilibrium to minimize the stress on the pipeline and structural support, both upwards and downwards.

Equation (1) is used to estimate the flow of hydrogen and energy transport in the deep ocean H_2 pipeline with different pressure

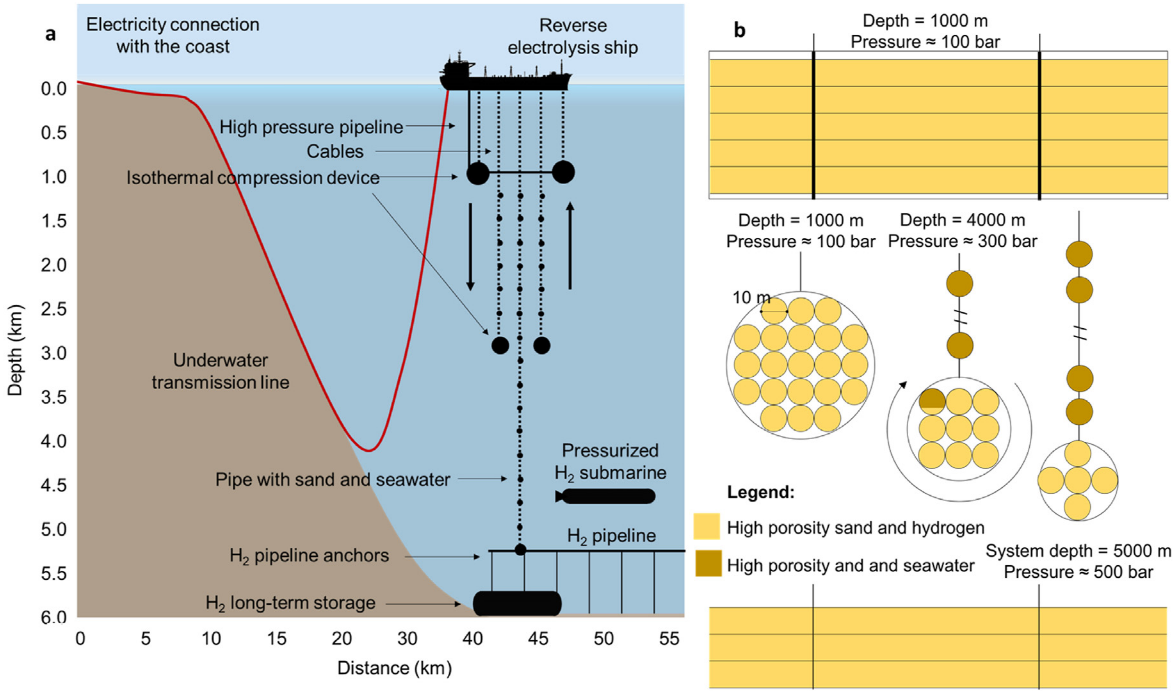

Fig. 3. Deep ocean H_2 isothermal compression, (a) connection between the coast, electrolysis ship, isothermal compression and deep ocean pipeline, (b) description of the isothermal compression devise.

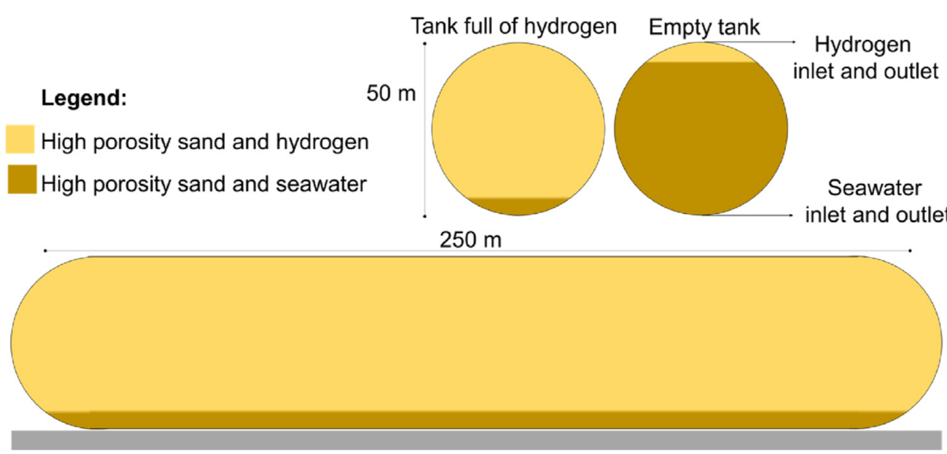

Fig. 4. Deep ocean H_2 long-term storage.

drops along the pipeline.

$$\Delta p = \frac{L \cdot f_D \cdot v^2}{2D} \quad (1)$$

where, Δp is the pressure drop of the hydrogen along the pipeline in Pa, L is the length of the pipeline in meters, assumed to be 5,000,000 m, f_D is Darcy friction factor (dimensionless), assumed to be 0.03 [55], v is the speed of the hydrogen in the pipeline in m/s, D is the diameter of the pipeline in meters, assumed to be 2 m.

A deep ocean H_2 pipeline with as little as 3 m diameter would transport around 200 GW of energy, which is a lot of energy to be transported from one place to another. For locations with significantly lower demand for H_2, this paper proposed to transport hydrogen in deep ocean H_2 submarines. The pressurized hydrogen deep-sea submarine, has the advantage of a transporting smaller amount of hydrogen. However, they are limited to small distances, as the weight of the submarine is 50–300 times heavier than the hydrogen transported.

2.1.4. Deep ocean H_2 submarine

The deep ocean H_2 submarine is a similar concept to the deep ocean H_2 pipeline, however, it consists of pipeline sections with are transported through a submarine (Fig. 6 (b)). This arrangement is particularly interesting to transport hydrogen to several locations with a small demand for hydrogen. The submarine is filled with hydrogen and sinks (Fig. 6 (a)). Some hydrogen flows into the outer pipeline removing some of the seawater so that the weight and buoyancy balance is met. Once the submarine reaches the final destination hydrogen is delivered and the submarine rises. Some water enters the outer pipeline to weight and buoyancy balance. The main issue of using the submarine for hydrogen transportation

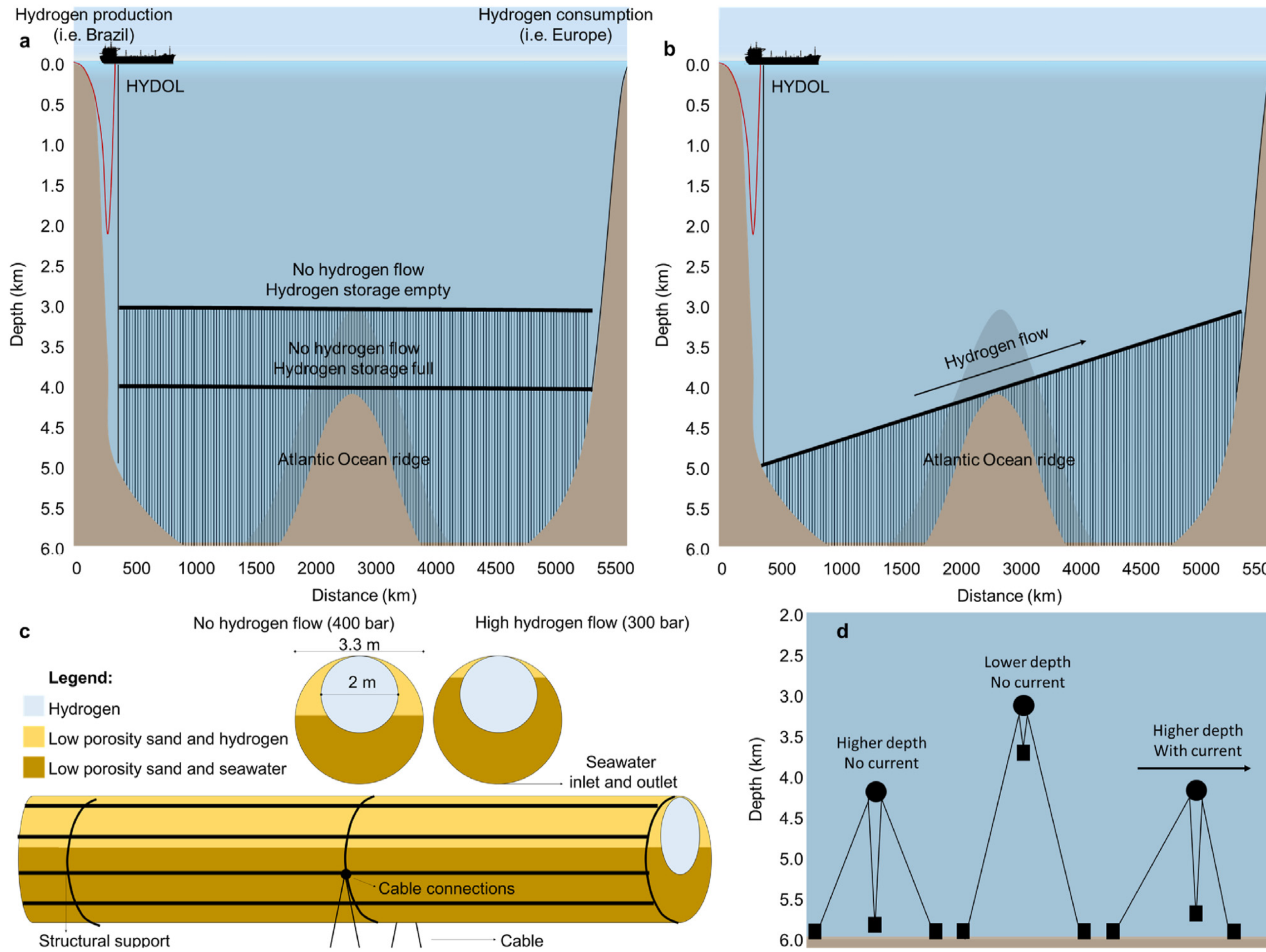

Fig. 5. Deep ocean H_2 pipeline, (a) without hydrogen flow, (b) with maximum hydrogen flow, (c) pipeline longitudinal and axial view, (d) pipeline and anchors axial view.

is that to transport 1 kg of hydrogen the submarine must transport 50–100 kg of sand and seawater (depending on the depth). This significantly increases the fuel costs and limits this technology to transport hydrogen in small distances. Another challenge for the submarine propulsion system is that there is no oxygen in the gaseous state on the deep sea, thus, if the submarine is powered by diesel or hydrogen, it must carry the oxygen required for propulsion. The most practical approach to do this is to carry liquid oxygen and to use fuel cells, which increase the energy conversion up to 70–80%. These types of submarines are named air-independent propulsion (AIP) [56]. Another option is to have nuclear submarines, however, they are more expensive and pose the threat of nuclear contamination of the deep ocean if there is an accident.

2.2. Weight and buoyancy equilibrium

For the proposed solution in this paper to be maintained at the designed depth, there is the need to add additional weight to counterbalance the low density of the pressurized hydrogen. This paper assumed that the cheapest and most appropriate material to counterbalance the buoyancy potential of hydrogen is sand. The deep ocean isothermal compression and deep ocean H_2 long-term energy storage solutions apply Equation (2). The deep ocean H_2 pipeline solution applies Equation (3), and the deep ocean H_2 submarine applies Equation (4).

$$V \times \rho_{SW} < V_S \times \rho_S + V_{SW} \times \rho_{SW} + V_H \times \rho_H + M \quad (2)$$

$$V \times \rho_{SW} > V_S \times \rho_S + V_{SW} \times \rho_{SW} + V_H \times \rho_H + M \quad (3)$$

$$V \times \rho_{SW} = V_S \times \rho_S + V_{SW} \times \rho_{SW} + V_H \times \rho_H + M \quad (4)$$

where, V is the volume of the proposed solution, ρ_{SW} is the density of seawater, V_S is the volume of sand in the proposed solution [57], ρ_S is the density of sand, which is assumed to be 1900 kg/m^3, V_{SW} is the volume of sand in the proposed solution, V_H is the volume of hydrogen in the proposed solution, ρ_H is the density of hydrogen, which varies significantly at different depths, M is the mass of the other components of the proposed solution.

3. Results

The arrangement proposed in this paper assumes that H_2 is replaced by seawater with the intent of compressing the H_2 or changing the buoyancy of the proposed solution. The mixing of seawater and hydrogen only makes sense if the solubility of H_2 in water is small, as the hydrogen solubilized in water would be wasted in the ocean. The solubility of hydrogen in the liquid phase is low, for example, mole fractions ranging from between 0.0004 and 0.0140 at 0 °C and pressures between P = 25 bar and P = 1000 bar [58]. Fig. 7 (a) present the change in solubility of H_2 in water at different pressures. This paper assumes that the solubility

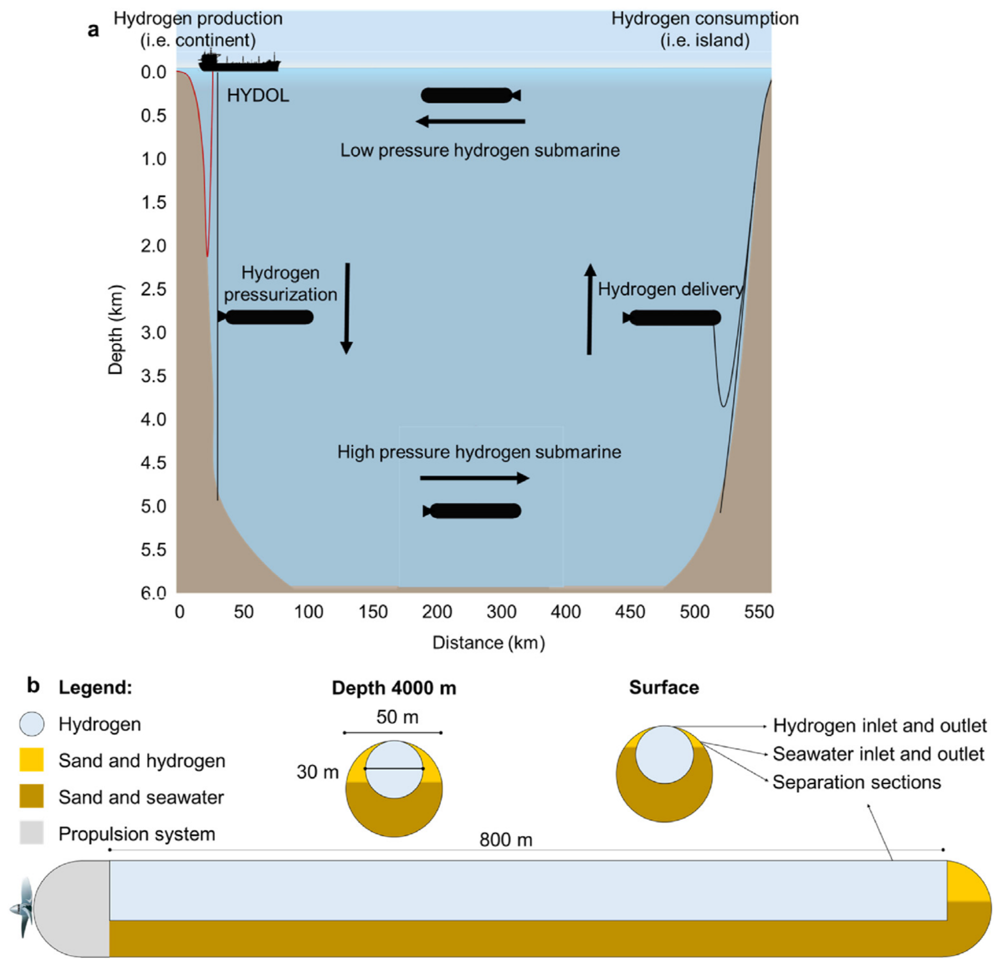

Fig. 6. Deep ocean H_2 submarine, (a) hydrogen delivery path, (b) submarine longitudinal and axial view.

of H_2 in seawater is the same as the solubility in water. Note, however, that given that seawater has already several other components dissolved, the solubility of H_2 in seawater is significantly smaller than in water. Assuming that the hydrogen is stored at 500 bar in the deep ocean, that xH_2 is 0.0064 and that the H_2 volume of the tank is replaced by seawater. This means that the loss of H_2 in water is only 0.64% for each storage cycle and 99.36% of the hydrogen is recuperated. Thus, this paper neglects the H_2 losses through the solubility in seawater.

The three components utilized to operate the proposed hydrogen compression, storage and transportation arrangements are hydrogen, seawater and a mixture of sand & hydrogen and sand & seawater. Sand was selected to increase the weight of the system to avoid it to rising the surface due to its low cost, inert and appropriate porosity to store hydrogen or seawater. Note that the density of the sand selected is slightly higher than the average sand, to reduce the volume and dimension of the pipelines. Fig. 7 (b) shows the change in density of hydrogen, seawater and sand at different depths.

Fig. 7 (c) presents the seawater volume variation for the outer pipeline in the deep ocean H2 pipeline and submarine, with the intent of maintaining the pipeline and the submarine in each depth. Note that the pipeline operational depths do not vary as much as the submarine. The submarine needs to have a high depth variation operation due to the need for filling up its tanks with oxygen on the surface if the submarine stays a long time without operating.

Assuming the pipeline proposed in Fig. 5 (c), the flow of energy in the deep ocean H_2 pipeline is presented in Fig. 7 (d). The flow of hydrogen is controlled by the slope of the pipeline. The flow of hydrogen in energy increases exponentially with the diameter of the pipelines. If the amount of hydrogen introduced to the pipeline is higher than the amount removed, the overall altitude of the pipeline reduces and hydrogen is stored within the pipeline. If the average pipeline pressure reduces from 400 bar to 300 bar, the pipeline can store 93,193 kg of hydrogen, which is equivalent to 2.174 TWh of electricity and the supply of electricity at a rate of 32 GW for 3 months.

An important aspect of the deep ocean H_2 submarine is the required ballast to avoid it rising to the surface. To maintain the weight and buoyancy capacity of the submarine in equilibrium, the low H_2 density must be compensated with the use of sand or other material to increase the weight of the submarine. Fig. 7 (e)shows the required weight multiplication factor, which is inversely proportional to the hydrogen density, shown in Fig. 7 (b).

The density and the costs of several materials have been compared in Fig. 7 (f) [59–63]. The larger the volume of the submarine, the higher the energy losses due to friction. This makes high-density materials interesting to be implemented in the submarine. However, due to the vast space available for the submarine to navigate and maneuver, the submarine can be very long and, thus, reducing the friction for moving underwater. Thus, wet desert sand is the most interesting alternative due to its low cost.

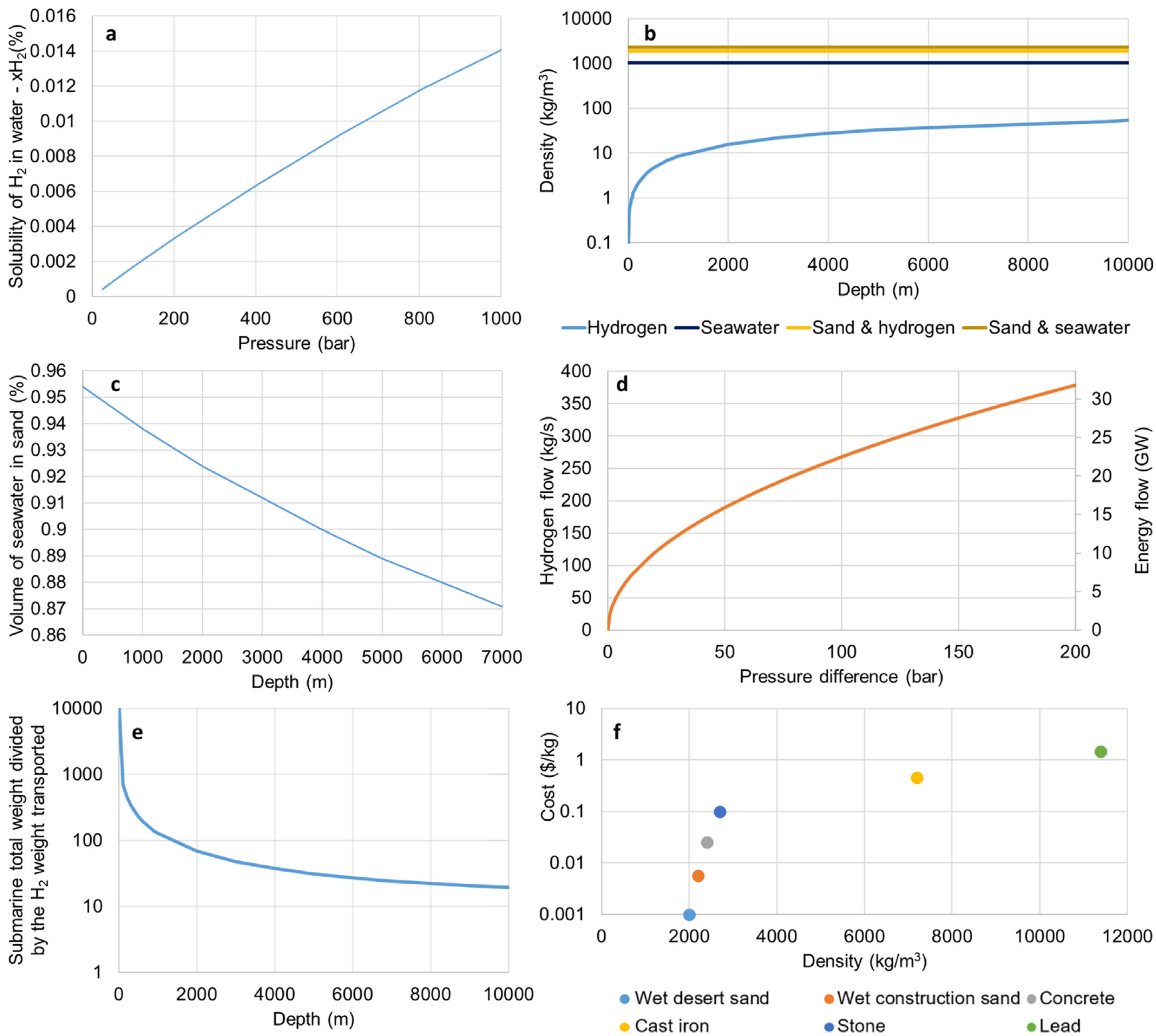

Fig. 7. Results, (a) Solubility of H_2 in water at 0 °C [58], (b) hydrogen and air density at different depths, (c) volume of seawater required in the outer pipeline in different depths, (d) flow of energy in the deep ocean H_2 pipeline with different slopes with the average pressure of the pipeline at 400 bar, (e) submarine total weight divided by the H_2 weight transported at different depths, (f) density and costs comparison of different materials [59–63].

3.1. HYDOL cost estimation

Table 1 presents a cost estimate for an arrangement that operates from 300 bars to 1000 bars with hydrogen.

3.2. HYDOL global potential

The global potential for HYDOL 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 data obtained from the GEBCO project [69]. The world potential consists of analysing the available depths where deep ocean H_2 long-term storage can be built close to the places with high demand (Fig. 8 (a)). It also finds the minimum depths required to transport hydrogen from one continent to another or through the coast of a continent, as shown in (Fig. 8(b–f)). The higher the depth available, the cheaper it is to transport hydrogen with a deep ocean H_2 pipeline and submarine. Fig. 8 (b) presents the ocean available at 1000 m deep, Figs. 8 (c), 2000 m deep, Figs. 8 (d), 3000 m deep, Figs. 8 (e), 4000 m deep, Figs. 8 (f), 5000 m deep. Analysing the potential, at 4000 m depth there is a significant amount of the ocean available to transport hydrogen and important bottlenecks that should be used to connect different countries and continents. Table 2 present the maximum depth allowed to transport hydrogen between locations.

Using the potential from Fig. 8 (d), showing the available ocean at 3000 m depth and the depth limits from Table 2, the global deep ocean H_2 pipeline is proposed in Fig. 8 (g). It consists of pipelines bordering continents and pipelines connecting continents. The criteria utilized were to keep the pipeline with a minimum depth of 3000 m and use the shortest distances to connect major continents. The coastal deep ocean H_2 pipeline sums up to 105,000 km, as shown in Table 3, which would cost around 40 billion dollars. Pipeline connection between continents of 85,700 km, as shown in Table 4, which would cost around 33 billion dollars. The sum of both pipelines networks is 191,300 km and 73 billion dollars. The

Table 1
Cost estimate for HYDOL system components with 70 MW and 7914 MWh capacity.

Component	Cost description	Cost
Deep ocean H_2 isothermal compression		
Pipes	21 HDPE pipes with 100 m. Extrapolating the costs in Ref. [64], it is estimated a cost of 120 USD per meter of pipe.	252,000 USD
Pipe sand	Desert sand for 1 USD per tonne to fill a volume of 164.850 m^3 [63]. Density of 1700 kg/m^3.	280,000 USD
Cables	5 km of cables, 285 KN, 8.3 USD/m each [65]. Assuming the cables must support 87,920 tons of sand requires 3026 cables. As the weight of the sand is distributed through the depth, the cable length is divided by 1.8.	69,773,000 USD
Motor/generator	Power capacity of 90 MW to have a compression cycle with an ascending time of 12 h and a power costs of 1000 USD/kW [66].	90,000,000 USD
Construction	30% of the equipment costs.	48,092,00 USD
Total project cost	–	208,397,000 USD
Compression cost	The system can compress isothermally 14,130 m^3 of hydrogen per day, from 100 bar to 500 bar, with an efficiency of 80–90%. The cost of compressing gas with conventional technologies is estimated at 85,948 USD/(m^3/d) [67], which makes deep ocean H_2 compression 6 times cheaper.	14,730 USD/(m^3/d)
Deep ocean H_2 long-term storage		
Pipe	HDPE pipe with 50 m, extrapolating the costs in Ref. [64].	750,000 USD
Pipe sand	Desert sand for 1 USD per tonne to fill a volume of 164.850 m^3 [63]. Density of 1700 kg/m^3.	835,000 USD
Construction	50% of the equipment costs, as equipment costs are very low.	800,000 USD
Total costs	–	2,385,000 USD
Hydrogen storage cost	The hydrogen storage capacity is 176,625 m^3 and 500 bar pressure.	14 USD/m^3
Energy storage costs	Assuming a generation efficiency of 70% and hydrogen density of 32.8 kg/m^3 at 500 bar, the energy storage capacity is 135 GWh.	0.018 USD/kWh
Deep ocean H_2 pipeline		
Pipes	Pipeline with 5000 km with an estimated cost of 120 USD per meter of outer pipe and inner pipe of 60 USD per meter [64].	99,375,000 USD
Pipe sand	Desert sand for 1 USD per tonne to fill a volume of 164.850 m^3 [63]. Density of 1700 kg/m^3.	46,500,000 USD
Containers	Assuming that 5% of the sand in the pipeline is required to keep the pipeline anchored to the deep sea. It is required 20,380 40FT containers.	14,266,000 USD
Container sand	Assuming that there are three 40FT containers to support the pipeline per 100 m.	1,380,000 USD
Cables	2 km of cables, 285 KN, 8.3 USD/m each [65]. Assuming the cables have to support 10% of the weight of the pipeline requires 80,000 cables are required, which is equivalent to 4 cables per container.	1,328,614,000 USD
Construction costs	30% of equipment costs	447,040,000 USD
Total costs	–	1,937,175,000 USD
Hydrogen transport	Assuming a generation efficiency of 70% and hydrogen density of 27.3 kg/m^3 at 400 bar, a pressure drop of 200 bar, a velocity of 4.4 m/s in the pipeline, equivalent to 13.9 m^3/s, 379 kg/s and 31.8 GW of energy.	60,917,453 USD/GW
Deep ocean H_2 submarine		
Pipes	Outer and inner pipe costs [64].	1,536,000 USD
Pipe sand	Desert sand for 1 USD per tonne to fill a volume of 2.180 m^3 [63]. Density of 1700 kg/m^3.	615,000 USD
Propulsion system	The submarine is assumed to use air independent propulsion (AIP), i.e. it carries liquid oxygen and generates electricity with the hydrogen in the submarine [68].	100,000,000 USD
Construction costs	30% of the equipment costs	30,000,000 USD
Operation costs	Variable and fixed costs are estimated to be 70% of total costs. Due to the need to transport large amounts of sand.	400,000,000 USD
Total costs	–	564,204,160 USD
Hydrogen transport	Assuming a generation efficiency of 70% and hydrogen density of 27.3 kg/m^3 at 400 bar, a 2 day trip, at 20 km/h, 500 km, and 7,5 GW of energy.	37,597,147 USD/GW

global potential for deep ocean H_2 submarine is limited for short distances and is shown in Table 5.

4. Discussion

An interesting advantage of the Hydrogen Oceanic Link proposed in this paper is that it consists of a multiple purpose Hydrogen Oceanic Link an electric transmission link, that can connect to offshore wind plants, hydrogen electrolysis ships, hydrogen power plant ships and other power plant ships, for instance, gas power plant ship, nuclear power plant ship, biomass power plant ship and others. This is particularly interesting because a country that has access to the sea will not have to build peaker power plants that operate at 2% of its capacity, particularly, during extremely cold or hot periods when electricity demand rises sharply. The power plant ship can be contracted and connected to the Hydrogen Oceanic Link and transmit electricity to the coast. Similarly, an electrolysis ship can generate H_2 when the price of electricity in the region is cheap so that electricity can be used to produce H_2.

5. Conclusions

This paper presented the proposed Hydrogen Deep Ocean Link to reduce the costs for hydrogen compression, long-term hydrogen storage, hydrogen intercontinental transportation, and transport between islands. This is the first time that the concept of storing hydrogen in the deep sea by replacing seawater with pressurized hydrogen is mentioned in the literature. These proposed arrangements benefit from the high pressures at the deep sea, which allows HDPE pipes to perform these services cheaply. The paper estimate that the investment costs for H_2 isothermal compression from 100 bar to 500 bar is 14,730 USD/(m^3/d), for long-term energy storage at 500 bar of 0.018 USD/kWh, for deep ocean H_2 pipeline of 60,917,453 USD/GW at 400 bar and 5000 km, and for deep ocean H_2 submarine of 37,597,147 USD/GW at 400 bar and 500 km. These costs are 6 times cheaper than business as usual hydrogen compression (compression turbines), 50 times cheaper than business as usual hydrogen long-term storage (surface pressurized storage tanks), and 3 times cheaper than then business as usual long-distance transportation (liquefied hydrogen). However, note

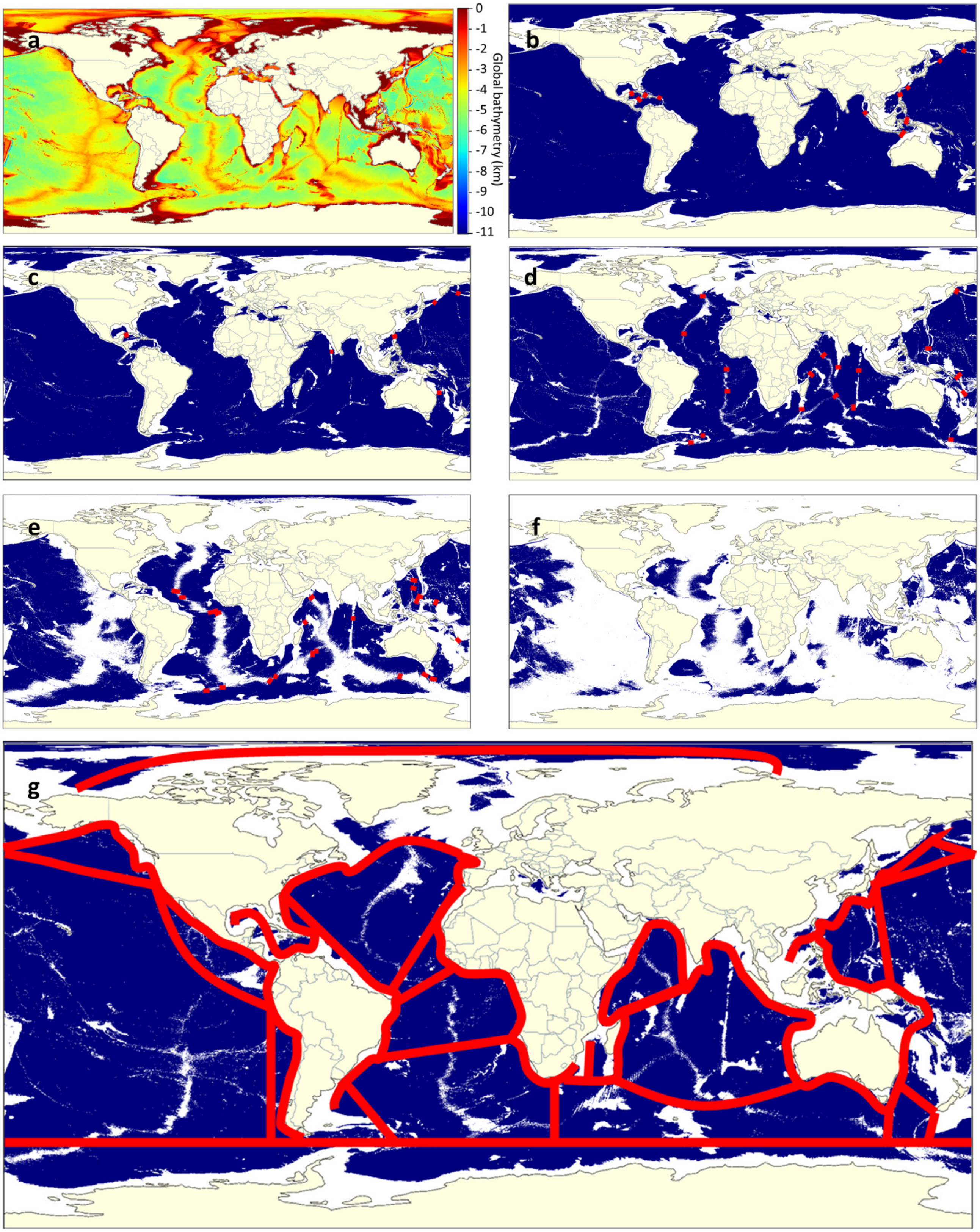

Fig. 8. Global potential for hydrogen ocean link [70], (a) global bathymetry, (b) ocean available at 1000 m deep, (c) 2000 m deep, (d) 3000 m deep, (e) 4000 m deep, (f) 5000 m deep, (g) proposed deep ocean H_2 pipeline.

Table 2
Maximum depth bottlenecks allowed to transport H_2 between locations.

Country/continent connections	Maximum depth (m)
Mediterranean Sea/Atlantic Ocean	900
Caribbean/Pacific Ocean	1650
Mexico, Equador, Peru, Chile/Pacific Ocean	3500
Colombia/Pacific Ocean	2800
Arctic Ocean/North Atlantic	835
Australia/Pacific Ocean	3600
Africa/Australia	3300
Atlantic/Pacific Ocean (Cape Horn)	3300
Middle East/Atlantic Ocean	4200
North America/Japan	4500
Americas/Europe/Africa	5200
China, Philippines/Pacific Ocean	4500

Table 3
Global deep ocean H_2 pipeline for connecting different continents.

Country/continent connections	Length (km)
Rio de Janeiro, Brazil/Namibia	5400
Paraíba, Brazil/Sierra Leone	2900
Rio Grande do Norte, Brazil/Portugal	5300
Suriname/North Carolina, USA	3400
California, USA/Peru	6400
Peru/South Pole Circle	6000
Cafifornia, USA/Tokio, Japan	8100
South Pole Circle	23,000
Papua, Tokyo, Japan	4100
Sydney, Australia/South New Zealand	1800
Perth, Australia/Cape Town, South Africa	8500
Pemba, Mozambique/Colombo, Sri Lanka	4700
Cape Town, South Africa/South Pole Cycle	2100
Tasmania, Australia/South Pole Cycle	1500
South America East Coast/South Pole Cycle	2500
Total	85,700

Table 4
Global deep ocean H_2 pipeline on continental coasts.

Country/continent connections	Length (km)
South America West Coast	7700
South America East Coast	9000
Caribbean	7000
North America East Coast	3000
North America West Coast	6100
Central America West Coast	5400
Asia West Coast	10,000
Oceania West Coast	12,000
Oceania East Coast	10,000
Southeast Asia & Middle East	9200
Africa West Coast	11,200
Africa East Coast	11,700
Europe	3300
Total	105,600

Table 5
Global deep ocean H_2 submarine for connecting different continents.

Country/continent connections	Length (km)	Depth (m)
Americas/Caribbean islands	50–500	1000–5000
Mediterranean Sea (Europe/Africa)	15–500	900–3000
India/Maldives	400–500	1500–2500
Marroco/Canary Islands	100–450	1500–2500
Between Oceania Islands	50–500	1000–3000

that liquefying hydrogen significantly reduces the overall energy storage efficiency of the system. The global potential for the shows that deep sea pipeline can be built surrounding the continents facilitating the transport of hydrogen within the continents, and connecting continents, resulting in a global sustainable energy grid.

Author contributions

Conceptualization, methodology, writing—original draft preparation, software, J.H.; formal analysis, writing—review and editing, visualization, A.N.; investigation, data curation, project administration, B.Z.; funding acquisition, resources P.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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