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Hydrogen balloon transportation: A cheap and efficient mode to transport hydrogen

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A R T I C L E I N F O

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A B S T R A C T

The chances of a global hydrogen economy becoming a reality have increased significantly since the COVID pandemic and the war in Ukraine, and for net zero carbon emissions. However, intercontinental hydrogen transport is still a major issue. This study suggests transporting hydrogen as a gas at atmospheric pressure in balloons using the natural flow of wind to carry the balloon to its destination. We investigate the average wind speeds, atmospheric pressure, and temperature at different altitudes for this purpose. The ideal altitudes to transport hydrogen with balloons are 10 km or lower, and hydrogen pressures in the balloon vary from 0.25 to 1 bar. Transporting hydrogen from North America to Europe at a maximum 4 km altitude would take around 4.8 days on average. Hydrogen balloon transportation cost is estimated at 0.08 USD/kg of hydrogen, which is around 12 times smaller than the cost of transporting liquified hydrogen from the USA to Europe. Due to its reduced energy consumption and capital cost, in some locations, hydrogen balloon transportation might be a viable option for shipping hydrogen compared to liquefied hydrogen and other transport technologies.

1. Introduction

The COVID pandemic and war in Ukraine have resulted in significant interest in the hydrogen economy [1]. The main interest in this switch in energy sources is to reduce CO_2 emissions and diversify energy suppliers and energy sources, increasing the energy security of countries dependent on fossil fuel imports [1]. Several sources, such as the International Energy Agency (IEA) and Blumberg, expect hydrogen will become a major energy carrier by 2050 [2]. One of the main impediments to the development of a global hydrogen economy is the intercontinental transport of hydrogen [3]. Regions that are expected to have a high demand for hydrogen, such as Europe and Japan, and regions with high production of hydrogen can be the USA, Australia, and Latin America. Thus, it is important to transport hydrogen from areas with a high availability of renewable energy sources to locations with a high demand for energy [4].

The main mean of intercontinental hydrogen transportation are liquid hydrogen, ammonia, methanol, and liquid organic hydrogen carriers (LOHC) [5–7]. The main challenges for liquid hydrogen are the high capital costs and energy consumption to liquefy the hydrogen (30 % of the energy carried in the hydrogen [8]), low volumetric density, and the fact that most hydrogen liquefaction processes use helium. Helium is produced as a by-product of the oil and gas industry, and by phase-out of oil and gas, helium will become a rare commodity [9,10]. The main issues with ammonia, methanol and LOHC are the high capital cost, and the fact that around 30 % of the energy transported will be required to transform these molecules back into hydrogen [11]. Another issue with methanol and LOHC is that they have carbon in their

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composition, and in a world with no fossil fuels, carbon will also be a scarce commodity. The following comprehensive reviews show that the main challenge for transporting hydrogen is its low volumetric density [12–15]. This paper proposes to use the low volumetric density as an advantage for transporting hydrogen in floating balloons. The weight of the hydrogen in the balloon, without cargo and ballast, i.e., gravimetric hydrogen density, could reach as much as 90 % of the total weight of the balloon. This possibly makes hydrogen balloon transportation, the hydrogen transportation mode with the highest gravimetric hydrogen density and the lowest volumetric hydrogen density [16].

Aviation is one of the hardest sectors to abate its carbon emissions. Although there may be a high demand for airship and balloon transportation, the high cost of helium reduces its viability, particularly when compared to hydrogen, which is cheap and abundant [17–19]. However, using hydrogen poses a greater risk [20], as it is flammable and explosive, as seen in the 1937 Hindenburg disaster [21]. Approximately 90 % of the documented mishaps using hydrogen airships involved fire, with the majority resulting in fatalities [22]. However, the chance of mortality with hydrogen airships would be significantly reduced if airship transportation, loading, and unloading were handled autonomously, (ii) ports were placed in remote places, and (iii) airships were not permitted to travel at low altitudes above major cities.

Several airship and balloon research projects are presently active. For example, the development of new designs [23,24], analysis of the dynamics of airship operation [25–30], ascension to the stratosphere using wing energy [31], the impact of thermal variations in ascent and descent trajectories [32,33], analyses of new materials for the construction of airships [34–36], such as aerogel [37], proposal of alternative propulsion systems [38], reduction of drag with shape optimization [39,40] experimental investigations [41], high altimetry pressurization and air conditioning [42]. Furthermore, airships have been thought to be constructed to be unmanned to lessen the danger of death, particularly if the airship employs hydrogen for buoyancy [43]. Solar powered airships [44–47], renewable energies powered airships [48–50], hydrogen powered airships [51], high altitude wind power generation with airships [52], solar turbine power stations with floating solar chimneys [53], energy storage alternatives for airships with regenerative fuel cell (RFC) [54,55], and the effect of high altitude on its energy system performance [56] have all received attention. Other studies have looked at the optimum airship routes to lower fuel usage, assuming already chosen destinations [43,57].

Hydrogen Balloon Transportation (HBT) has been first proposed in Ref. [58]. [58] focused on using the Jetstream (6–14 km altitude) to push the hydrogen balloon from west to east, particularly in latitudes of 30 or -30°. However, the paper does not attempt to find the optimum altitude for transporting hydrogen. This is the second article to investigate the possibility of transporting hydrogen in balloons pushed by prevailing winds. Its main focus is to find the optimum altitude for balloons to transport the hydrogen with the intent of developing a future, clean, affordable hydrogen transportation industry. It also estimates the costs for transporting hydrogen with balloons and proposes the main routes for transporting hydrogen with balloons. There are five sections to the paper. Section 2 describes the HBT technology and discusses the problems and benefits of transporting hydrogen in balloons. Section 3 describes the methods used to determine the best altitude for hydrogen balloons to be propelled by the wind. Section 4 presents the paper's results. Section 5 discusses critical issues and alternatives to transporting hydrogen in balloons. Section 6 brings the paper to a close.

2. Hydrogen balloon transportation (HBT)

HBT consists of delivering hydrogen as a gas at ambient temperature using balloons. This significantly reduces the energy required to convert or pressurize hydrogen gas, and to transport it, as the balloons are carried by the wind. Fig. 1 presents the proposed HBT process. The process is divided into four steps, which are described as follows: (i) Green H_2 production: consists of producing green hydrogen in locations with cheap and abundant solar and wind power potential. (ii) H_2 balloon transportation: Before filling the balloons with hydrogen, several weather forecasts should be investigated, and the balloon should only be filled with there are several paths/altitudes that the balloon can utilize to reach its destination. The hydrogen balloon transportation process starts with the hydrogen from the grid being depressurized into 1 atm pressure to fill up the balloon. A pressure reduction turbine could be used to recover some of the energy in the pressurized hydrogen [59]. The balloon is attached to several anchors and ballast that keep it from rising in the air until it is fully filled. When the balloon is fully filled, it is detached from the anchors and raised to its designed flying altitude. Compressed hydrogen, cargo and water could be used as ballast. Water is added so that the balloon can release it to gain altitude if required. Compressed hydrogen and cargo are added to increase the weight of the balloon and control its altitude. (iii) Green H_2 delivery: To ensure that the balloon will land safe and close to a hydrogen delivery point, the delivery point should be on the ocean or by the coast. When it is close to the coast, the balloon will drop ropes, and a support ship will guide the balloon to a delivery point (Fig. 2 a). The support ship will also pull down the balloon to the surface (Fig. 2 b). When the balloon arrives at its destination, it is connected to a pressurized hydrogen network. The hydrogen is extracted from the balloon, pressurized and injected into the network. While the balloon is emptied, it is twisted slightly, folded, and stored to be shipped back to where the hydrogen is produced. (iv) Empty balloons returned by ship: After the balloons are emptied, they are put into a container. The container is then loaded onto a ship and transported back to its starting location. This is one of the reasons why we

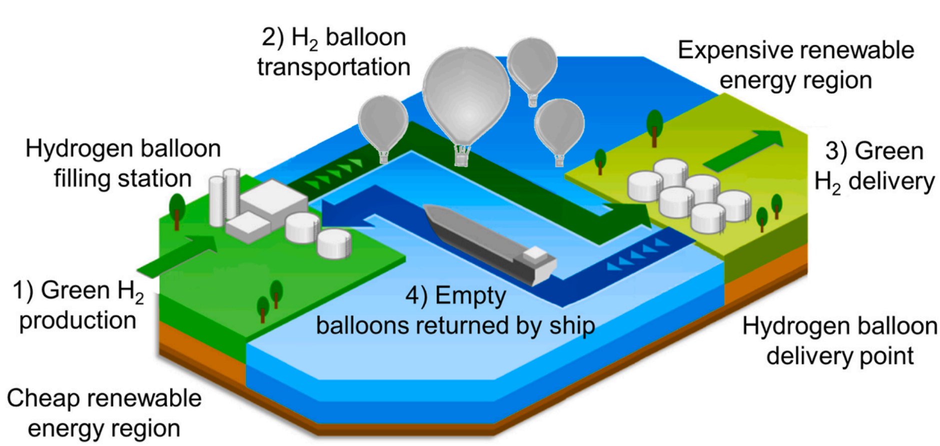

Fig. 1. Hydrogen balloon transportation (HBT) description.

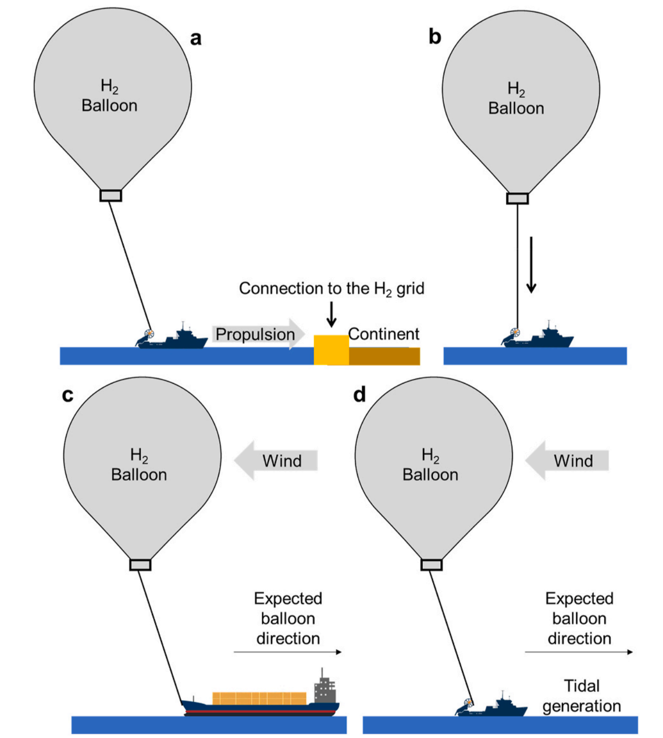

Fig. 2. The hydrogen balloon (a) can be transported by a support ship to the H_2 network (b) can be lowered by the support ship, (c) can reduce fuel consumption of passing ships and (d) can generate electricity with tidal power in the support ship.

propose the use of balloons. Airships would not be practical to be transported via containers.

To increase the safety of this transportation mode, hydrogen balloons should only fly over the ocean. This is convenient because support ships could assist in the transportation of the balloons in any direction on the ocean. This would not be possible on the continent. If the weather forecast is wrong and the balloon is blown away from the path to its destination and ends up flying over the continent, the balloon could be guided to land to minimize the risks of incidents. If the balloon is flying in the wrong direction, it could be connected to support ships, which would lower the balloon's altitude to reduce the wind speed and push the balloon in the right direction (Fig. 2 c). Alternatively, the balloon can connect with a passing ship and provide additional thrust to the ship below, while at the same time slowing down the balloon (Fig. 2 c). The balloon can have an exclusive boat on the ocean to guide it to catch the most appropriate wind to reach its destination. In this case, the support ship can generate tidal energy to slow down the balloon (Fig. 2 d). Tidal power would be generated by the ship's propeller/generator, which would operate as a propeller if the ship wants to accelerate and as a generator if it intends to slow down the ship. The hydrogen balloon filling stations and delivery points should be located on land near the coast or on offshore platforms linked to a hydrogen pipeline network. The second option is better, as it reduces the risks of the balloon flying over the continent and because the balloon could float on the ocean while the hydrogen is being extracted from it. To reduce the risk of explosion, hydrogen balloons should not have propellers or other moving parts. Following these proposals, the risk of incidents with hydrogen transportation is insignificant.

3. Methodology

Fig. 3 presents the methodological framework applied in the paper. It is divided into three steps. Step 1 presents a description of the HBT concept. It describes the HBT process, its components, and operation. Step 2 presents the methodology to estimate the ideal altitude for flying the balloons. It estimates wind patterns, pressure, and temperature variations at different altitudes. Then it estimates the ideal hydrogen balloon flight altitude. Step 3 describes the potential for HBT. It estimates the costs of transporting hydrogen in balloons, runs a case study for transporting hydrogen from North America to Europe, presents other potential locations where this technology can be applied, and presents several other services that can be combined with the transport of hydrogen.

3.1. Ideal altitude for hydrogen balloon transport (HBT)

The major characteristics studied in this research are to explore how wind speeds and explore impact hydrogen transportation. The wind speed data evaluated is from the European Centre for Medium-Range Weather Forecasts (ECMWF) Pressure Levels Reanalysis ERA5 data [60]. The wind speed is separated into two components: wind speeds from west to east (W-E) and wind speeds from north to south (N–S). This paper only considers wind speeds from west to east and east to west, which are the directions with the highest predomination. Wind speeds from west to east are denoted with a positive sign, for example, from New York to London. Wind speeds from east to west are denoted with a negative sign, for example, from Africa to South America. To present a case study of possible scenarios for Hydrogen Balloon Transportation

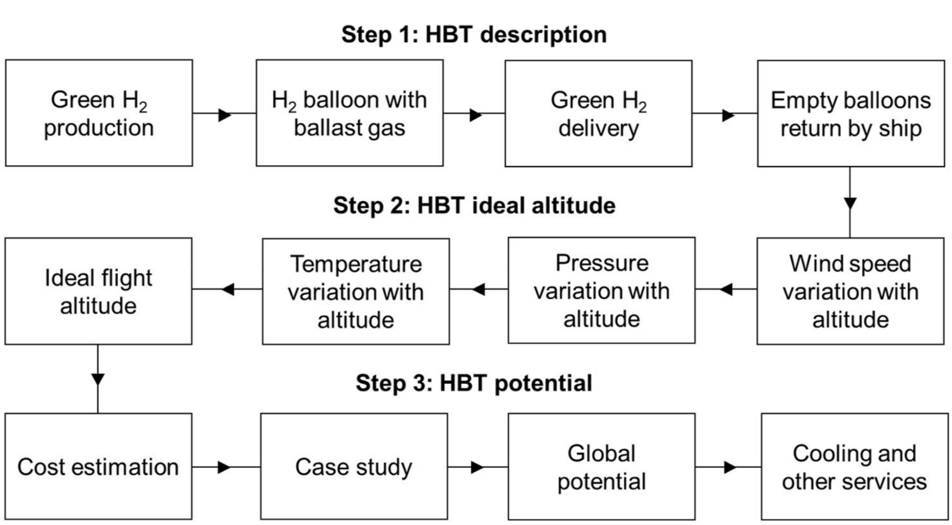

Fig. 3. Methodological framework for hydrogen balloon transportation (HBT).

from the USA to Europe, the Habhub model [61] hase been applied (https://predict.sondehub.org/). The Habhub model is a tool developed by the Cambridge University Space Flight to predict the flight path and landing location of balloons using data from the NOAA GFS models.

4. Results

Fig. 4 consists of the average monthly W-E wind speed data at pressure levels ranging from 0.9 to 0.6 bar with a 0.5° resolution. Fig. 4 (a) presents the highest speeds from east to west in intertropical areas at 1000 m. Fig. 4 (d) presents the highest wind speeds from west to east at 30 to 60 and -30 to −60° latitude. The average horizontal wind speeds at these altitudes vary from 83 km/h below Africa at 4000 m altitude to −62 km/h in Antarctica.

Fig. 5 presents the maximum and minimum average horizontal speeds at 1000 m, 2000 m, 3000 m and 4000 m altitudes. Combining these different altitudes is relevant because the balloons may change height and pressure levels to fly at higher speeds or change their flight direction. The pressure levels with the highest (Fig. 5 (a)) and lowest (Fig. 5 (b)) wind speeds are chosen. The speeds above 4000 m are not described in this paper because they are already presented in Ref. [58]. Table 1 shows the paths for HBT at altitudes below 4000 m. The only paths that the origin has a high renewable energy potential and that the destiny has a high hydrogen demand are between North America to Europe, South America to China and Central America to China. However, the distance from North America to Europe is 3500 to 5000 km, and the distance from South America and Central America to China is 15,000 to 20,000 km, which makes North America to Europe the most likely path for HBT.

Fig. 6 (a) presents the hydrogen balloon pressure at different altitudes. The higher the altitude, the lower the hydrogen pressure in the balloon, thus, the less hydrogen is transported by volume in the balloon. The pressure variation was taken from Ref. [60] and vary from 0.9 bar at 900 m to 0.15 bar at 13.500 m. On average, an increase in 1 km altitude results in a reduction in pressure of 0.06 bar. Fig. 6 (b) presents the atmospheric temperature variation with altitude in the atmosphere taken from Ref. [62]. The temperature varies from 17 °C on the surface to −70 °C at 13.5 km, then it is maintained at −70 °C. Note that the atmospheric temperature profiles vary significantly with latitude and season and should be adjusted to each application. The higher the temperature difference between the surface and the stratosphere, the smaller the balloon volume variation with altitude, and the better it is to

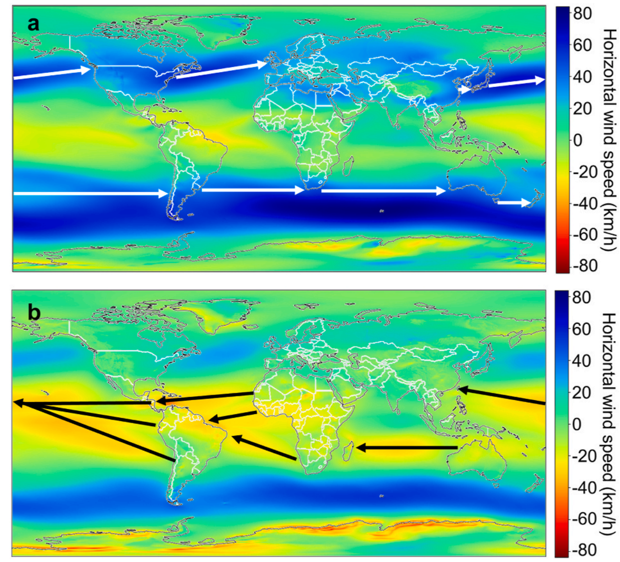

Fig. 5. (a) Maximum and (b) minimum horizontal speeds at 1000 m, 2000 m, 3000 m and 4000 m altitudes.

transport hydrogen at high altitudes. Fig. 6 (c) presents the hydrogen balloon volume at different altitudes assuming the pressure in Fig. 6 (a) and temperature in Fig. 6 (b). A hydrogen balloon with 1 km^3 at 0.15 bar pressure transports the same amount of hydrogen as a balloon with 0.23 km^3 at 0.9 bar, which is a volume 4.3 smaller. On average, an increase in 1 km altitude increases in volume of 0.061 km^3. Fig. 6 (d) presents the maximum average west to east horizontal speed in Fig. 4 and [58]. The wind speed increased from 53 km/h on the surface to 165 km/h at 11.7 km altitude. That is an increase of 9.6 km/h per 1 km altitude. Then it reduces to 115 km/h at 16 km altitude. Fig. 6 (e) presents the speed/volume index, which consists of dividing the maximum average west to east horizontal speed (Fig. 6 (d)) by the hydrogen balloon volume (Fig. 6 (c)). The speed/volume index shows how fast hydrogen can be transported with a given balloon volume at different altitudes. The best altitudes to transport hydrogen by balloon ranges from the surface to 10 km altitude, and the best altitude is 6.2 km. The higher the altitude, the higher the wind speeds, but less hydrogen is transported per volume. The speed/volume index only applies to HBT flying west to east. One

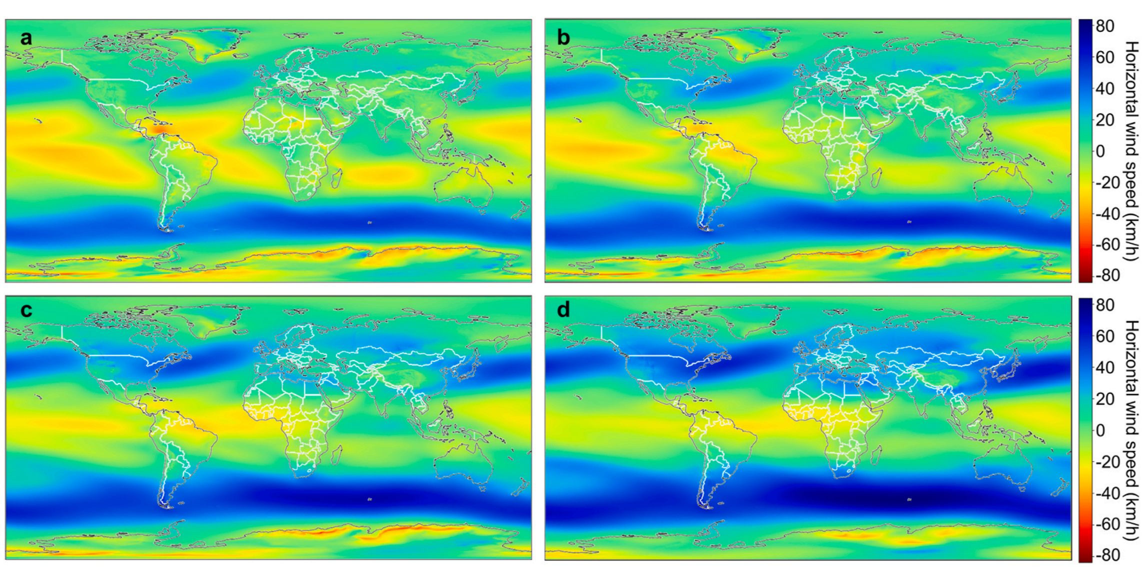

Fig. 4. Average horizontal wind speed at (a) 0.9 bar and 1000 m altitude, (b) 0.8 and 2000 m, (c) 0.7 and 3000 m, (d) 0.6 bar and 4000 m. Data source ERA5, ECMWF [60].

Table 1
Possible paths for hydrogen balloon transportation at altitudes below 4000 m.

Direction	Origin	Destiny	Origin renewable potential	Destiny hydrogen demand
West to east Fig. 5 (a)	North America	Europe	High	High
	Japan	North America	Low	High
	South America	Africa	High	Low
	Africa	Australia	High	Low
	Australia	New Zealand	High	Low
	Australia	South America	High	Low
East to west Fig. 5 (a)	Australia	Africa	High	Low
	Africa	Central America	High	Low
	Africa	South America	High	Low
	South America	China	High	High
	Central America	China	High	High

aspect that is not included in the analysis is that wind speeds at higher altitudes have a more predominant wind direction west to east, which favors transporting hydrogen at higher altitudes. However, a ship on the sea can push the balloon at low altitudes.

Out of the existing hydrogen balloon paths shown in Fig. 5, the USA to Europe is the most promising path for HBT. This is because the USA has significant renewable potential to supply its internal demand and to export the excess production to Europe. Fig. 7 presents the average horizontal wind speed from the USA to Europe. The circles in red represent possible hydrogen balloon filling stations. The circles in blue represent possible hydrogen balloon delivery points. Hydrogen or electricity also could be generated in Central America and South America and transported by pipeline or transmission lines to the hydrogen balloon filling stations in the USA.

Fig. 8a presents the results for the Habhub model on December 18, 2022 from 20:25 GMT [61], assuming the start location from Massachusetts, US, and a constant flight altitude of 1000 m (blue line) and 3000 m (green line). The results consist of 180 h (7.5 days) of predictions using the GFS weather prediction model. The runs start from 20:25, 21:25, 22:25, 23:25 GMT December 18, 2022 and 00:25, 01:25, 02:25, 03:25, 04:25, 05:25, 06:25, 07:25, 08:25, 09:25, 10:25, 11:25, 12:25, 13:25, 14:25, 15:25, 16:25, 17:25, 18:25, 19:25 GMT December 19, 2022. That is 24 scenarios, one per hours after the starting time of

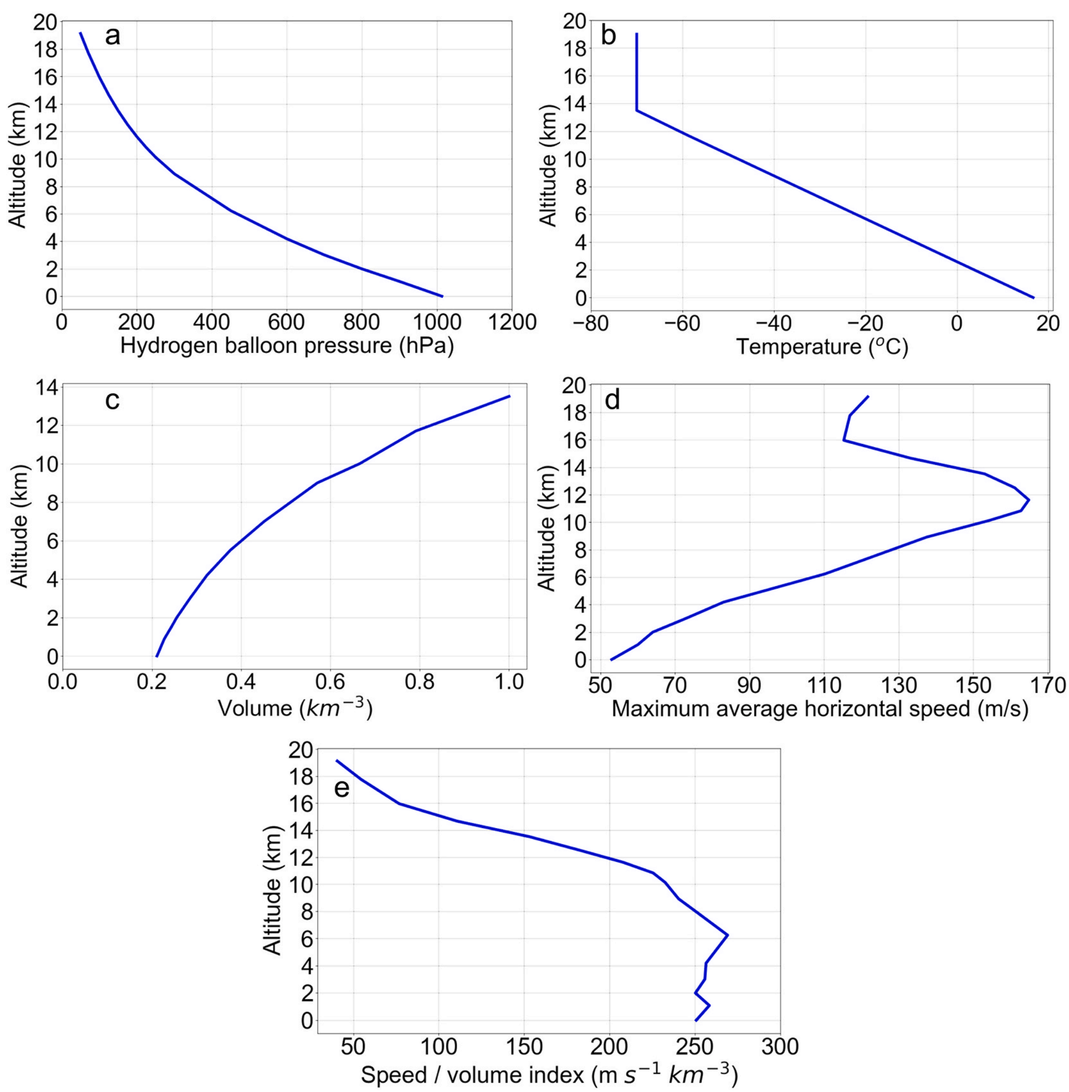

Fig. 6. Altitude variation vs. (a) atmospheric pressure [60], (b) atmospheric temperature [62], (c) balloon volume, (d) maximum average west to east horizontal speed, (e) volume vs. average speed.

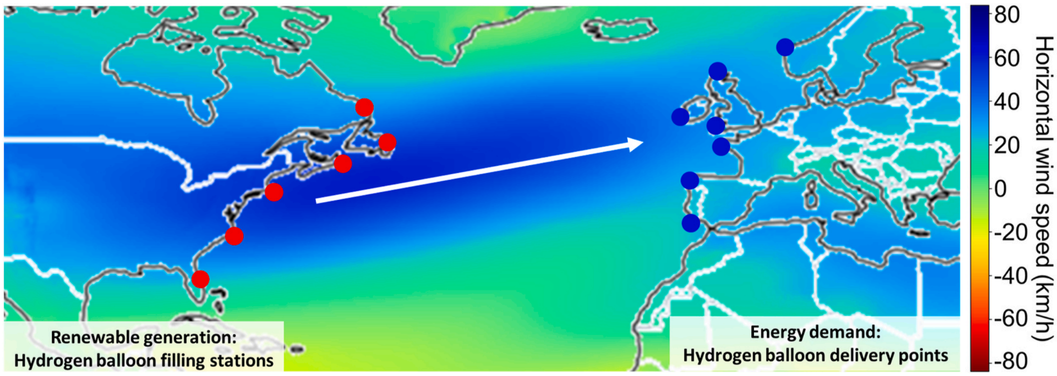

Fig. 7. Average horizontal wind speed from the USA to Europe.

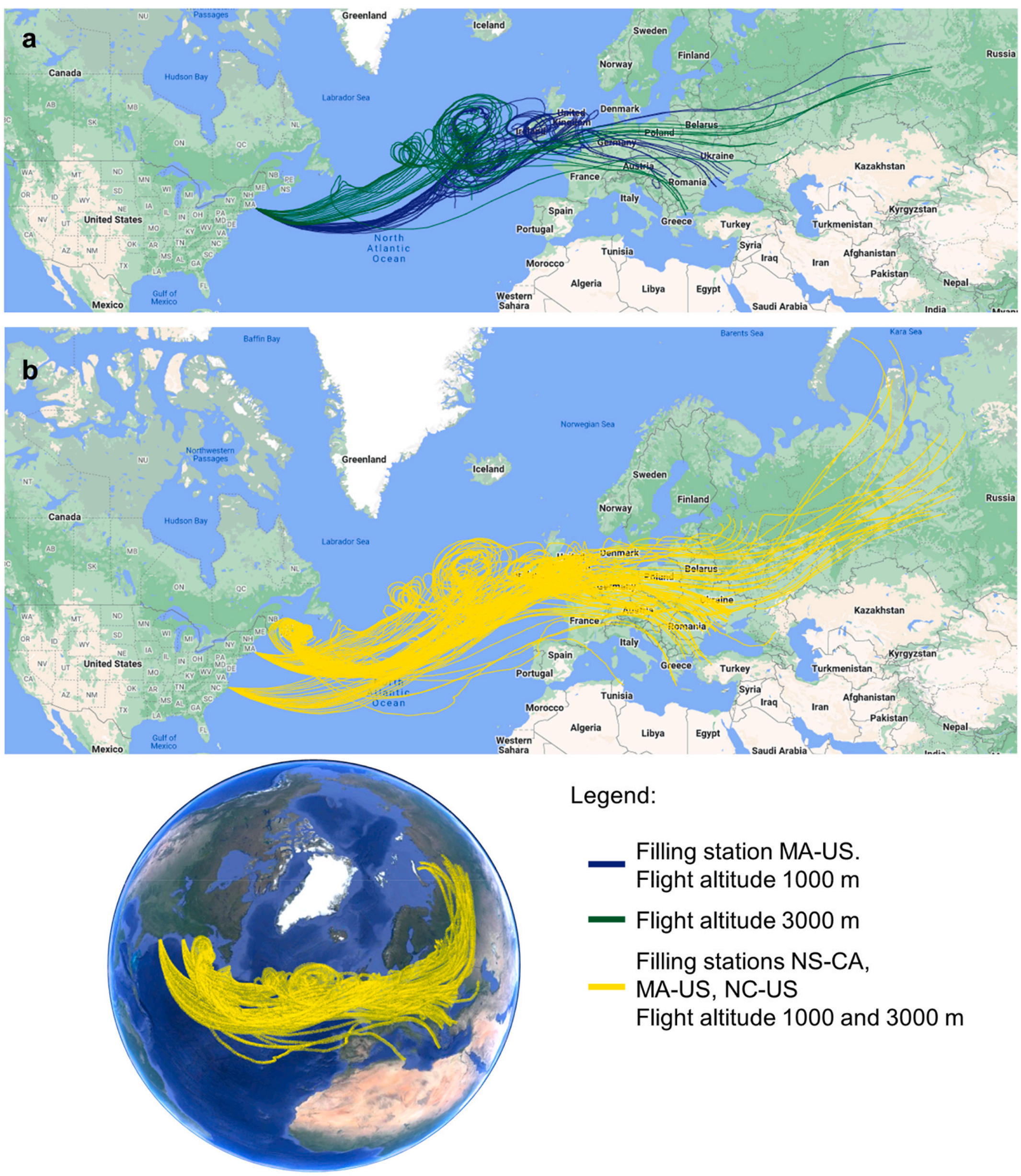

Fig. 8. Hydrogen balloon path prediction from (a) MA-US, at 1000 m (blue) and 3000 m (green) [63], (b) NS-CA, MA, NC-US at 1000 and 3000 m (yellow) [64]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

20:25 GMT, December 18, 2022. As can be seen, there is a significant difference in the balloon's flight direction at different altitudes, particularly at the beginning of the flights. Out of the 24 flights at 3000 m, described in Figs. 8a and 17 (66 %) have reached Europe in less than 7.5 days, and 8 have not. Out of the 24 flights at 1000 m, 16 (66 %) have reached Europe in less than 7.5 days, and 8 have not. Fig. 8b. Out of 144 flights, 126 (87.5 %) have made it to Europe, 18 have not.

Table 2 shows the distance and travel time between the cities shown in Fig. 8. The average travel time of the balloons that reached Europe is 4.8 days. Compared with a ship traveling from Massachusetts to Cork, Ireland, at a speed of 20 knots (37 km/h) and a distance of 5413 km, the trip time is 6.1 days [65]. It should be noted that this estimate does not account for the time it takes the airship to ascend to the stratosphere, descend, unload, and load, security checks, and so on. It solely considers the wind speeds in the atmosphere.

4.1. Cost estimate

Table 3 presents the cost estimate for HBT. The three main costs are the balloon, the return ship to carry the empty balloon back, and the support ship to guide the balloon to its destination. The estimated investment cost for one hydrogen balloon transportation with 1 km^3 is 260 million USD. This results in a hydrogen transportation cost of 0.08 USD/kg, which is, on average, 12 times cheaper than the cost of transporting H_2 as liquid hydrogen [66]. The hydrogen balloon transportation altitude impacts the costs of transportation in two main ways: the higher the altitude, the higher the speed of the balloon, but the lower the hydrogen pressure. Thus, the ideal altitude to reduce the transportation cost will depend on the climate conditions and forecasts before releasing the balloon. The hydrogen balloon transportation operation and cost estimates in this paper assume average weather conditions, which does not represent actual weather conditions accurately. For example, during periods of high wind events, the balloon cannot be charged or discharged, and the balloons cannot fly over boisterous winds, large tropical storms, hurricanes and other harsh conditions along the trajectory. Thus, detailed operational scenarios should be developed for each project where hydrogen balloon transportation should be considered and their impact on transportation cost should be investigated.

5. Discussion

Given the large number of debate points that must be elaborated on, this part is separated into the subsections listed below. The summary of the advantages and disadvantages of airships and balloons is presented in Table 4.

5.1. West to east routes

There are certain anomalies to using the jet stream for airship and balloon transportation. One key concern is that the airship must go around the planet in only one direction, from west to east. For example, an airship could travel from New York to London, but the return journey would be extremely tough. Another factor to consider is that the majority of the energy used in airships and balloons is for a lift to the stratosphere as the jet stream drives them to their eventual destination. Therefore, long-distance routes should be prioritized. There are three main approaches to controlling the flight direction. The most important strategy is to wait for appropriate wind directions and speeds that will push the balloon to its destination. The second is to change the altitude of the balloon. Different altitudes have different wind directions and speeds. The third is to attach the balloon to a ship and sail to the destination.

5.2. Natural gas

The same approach for transporting hydrogen with balloons can be applied to transporting natural gas. This could be applied to transporting natural gas from the USA to Europe now that Europe cannot rely on Russian gas supplies. However, the benefits of transporting natural gas with balloons are significantly smaller than those for transporting hydrogen, as natural gas is significantly simpler to liquefy, and liquid natural gas has a volumetric energy density three times larger than liquid hydrogen. The density of natural gas is 0.68 kg/m^3, while the density of air is 1.29 kg/m^3.

5.3. Planes vs. balloons

Transoceanic flights usually happen between 8 and 12.5 km altitudes. Hydrogen balloon transportation should fly at a maximum altitude of 6 km to maintain a relatively high hydrogen pressure in the balloon. Thus, they should not disturb the air flight while crossing the ocean. However, care should be taken when the balloons are close to the shore, particularly if there are airports close to the coast. The balloons should have visible flashing lights to indicate their position.

5.4. Wind drag

The variable drag of the airship design should be as high as feasible. If the jet stream is pulling the airship away from its target, the drag should be lowered as much as feasible. The drag may be adjusted using adjustable sails. It should be emphasized that a structure longer than 1 km is exceedingly fragile. During a storm, if there is a significant variation in wind velocity between the front and back of the airship, it might be ripped in half. As a result, it should be made to be sturdy enough to endure shear induced by winds from various directions. New material innovations may be able to ensure the robustness and resilience required to withstand severe storms.

5.5. Long-term energy storage

HBT could be used to store hydrogen seasonally or perennially. If a balloon is released near the north or south polar circle while the wind pattern is blowing in the direction of the north or south pole, the balloon will become trapped in the north and south poles and will circle the north and south poles circles. When hydrogen is required, it can be pushed by supporting ships when the balloon flies over an ice-free ocean. Other long-term energy storage solutions are presented in Refs. [69–75].

Table 2
Distance and travel time between North America to Europe.

Origin	Distance to Europe	Altitude	Shortest trip (days)	Longest trip (days)	Maximum horizontal speed (km/h)	Maximum speed (km/h)	Minimum speed (km/h)	Average speed (km/h)
Nova Scotia, Canada	3580	1000	4.43	5.34	97.3	116.9	8.2	48.9
		3000	3.59	4.39	124.2	133.2	7.1	54.4
Massachusetts, USA	4505	1000	3.42	did not reach	118.4	130.9	3.3	52.1
		3000	6.08	6.84	94.3	110.0	0.5	45.0
North Carolina, USA	5320	1000	did not reach	did not reach	85.7	96.0	0.9	49.9
		3000	3.21	did not reach	109.4	109.4	0.8	55.47
Average			4.15	5.52	104.9	116.1	3.5	51.0

Table 3
Cost estimate for hydrogen balloon transportation.

Component	Cost description	Cost
Balloon	The cost of the balloon is mainly the envelope cost. The envelope proposed for the balloon is ultra-high molecular weight polyethylene (UHMWPE) fabric. Assuming a spherical, 1 km^3 balloon at 6 km (maximum altitude) and 0.52 km^3 at the surface, the balloon envelope area is 4.8 km^2 at a cost of 42 USD/m^2 and a weight of 816 tons. We assumed double the cost of the envelope in Ref. [67] to include other equipment and the manufacturing costs. The balloon is assumed to fly at an average 3 km altitude, where the volume of the balloon is 0.70 km^3.	200 million USD
Return ship	The return ship is used to store the balloon so that it can be transported back to the original location. It should have a large volume to accommodate the balloon's volume. Each return ship can accommodate up to 4 balloons.	40 million USD
Support ship	The support ship is used to help the balloon reach the hydrogen delivery point. Each support ship can service up to 8 balloons.	20 million USD
Total project cost	–	260 million USD
Operation and management costs	The yearly operation and maintenance costs are assumed to be 30 % of the investment costs. This includes the energy costs to operate the balloon and the ship. To estimate the energy consumed by the balloon, we assume that it will rise to 6 km altitude and then return to the surface. The energy consumption consists of the electricity required to compress 43,750 tons of hydrogen at 0.47–1 bar. Using the equations in Ref. [68], and assuming that hydrogen is used in fuel cells with 70 % efficiency, around 1.4 % of the energy within the balloon is required to compress the hydrogen. Assuming a cost of 1 USD/kg of hydrogen, it is equivalent to a cost of 2 million USD per year. This does not include the energy that might be required to push the balloon horizontally with support ships.	78 million USD per year
Lifetime	10 years	–
Discount rate	Assuming a 10 % interest rate, the discount factor in 10 years is 9.	–
Hydrogen weight per balloon	At 3 km altitude, the pressure is 0.7 bar, temperature -3 °C, density 0.0625 g/L and the balloon has 0.7 km^3 of hydrogen, which is equivalent to43,750 tons of hydrogen. For comparison, a liquid hydrogen tanker, which is the same size as an LNG tanker, would transport 6000 tons of hydrogen.	–
Hydrogen transportation cost	Assuming that the balloon takes an average of 12 days to deliver the hydrogen from the US to Europe and return, a balloon can deliver hydrogen 30 times per year, equivalent to 1,312,500 tons of H_2. The hydrogen transportation cost is estimated at 0.08 USD/kg (260,000,000/9 + 78,000,000)/1,312,500,000). This is 12 times smaller than current cost estimates for liquid hydrogen transportation from the US to Europe at 1 USD/kg [66].	0.08 USD/kg of H_2 transported

Table 4
Summary of advantages and disadvantages of airships and balloons.

Advantages	Disadvantages
Energy can be generated using solar arrays or the hydrogen used for lift.	The jet stream flows predominantly from west to east. Thus, the airship route is unidirectional.
Cost estimation is within the cost of marine shipping and aircraft.	Airships and conventional long-haul planes will share similar flight altitudes, which could contribute to accidents between balloons and airplanes.
The airship stores the cold temperature from the stratosphere, and it can be used for cooling services on the ground.	Wind drag and storms have the potential to destroy the airship.
Low stratospheric temperatures can increase the efficiency of hydrogen liquefaction.	Global warming can reduce the jet stream strength in the Northern Hemisphere and increase the frequency of extreme weather.
Hydrogen electricity generation produces water, which can be used to create artificial precipitation.	Energy consumption by airship is estimated to be four times higher than in maritime shipping.
Airships can be used to facilitate the launch of objects into space.	

5.6. Global potential for hydrogen balloon transportation

According to IRENA, IEA, Bloomberg, and the Hydrogen Council, the demand for hydrogen in 2050 will be around 600 million tons per year [2,76]. Assuming that 10 % of this hydrogen will be transported with balloons, this would require around 60 balloons to transport this hydrogen and an investment of around 16 billion USD. Alternatively, if the balloons are designed with a volume of 0.1 km^3 at a 6 km altitude, it would require around 600 balloons to fulfill the demand for hydrogen balloon transportation.

6. Conclusion

This paper focused on finding the ideal altitude to transport hydrogen in balloons, which is ~6.2 km. Hydrogen could also be transported at altitudes ranging from 1 to 8 km. The parameters that most impact HBT are the predominant wind patterns, the wind speeds, pressure, and temperature at different altitudes. The most promising paths to transport hydrogen with balloons are from North America to Europe and from South America to China, given the abundance of renewable energy at the exporting region and the high demand for hydrogen in the density. However, due to its proximity, North America to Europe is a more feasible option. We propose HBT be considered only over the ocean. This is done to reduce the possibility of incidents and because a support ship can guide the balloon navigate along the way. The cost of HBT is estimated at 0.08 USD/kg, which is around 12 times smaller than the cost of transporting liquid hydrogen from the USA to Europe. The prospect of inexpensive and clean intercontinental hydrogen transportation would be advantageous for establishing a worldwide hydrogen economy. This would eventually facilitate the broad adoption of intermittent renewable energy technologies such as solar and wind and promote sustainable development in different world regions.

Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

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The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

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