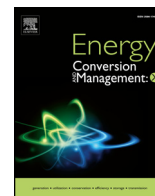




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## Using the jet stream for sustainable airship and balloon transportation of cargo and hydrogen

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## ABSTRACT

The maritime shipping sector is a major contributor to CO<sub>2</sub> emissions and this figure is expected to rise in coming decades. With the intent of reducing emissions from this sector, this research proposes the utilization of the jet stream to transport a combination of cargo and hydrogen, using airships or balloons at altitudes of 10–20 km. The jet streams flow in the mid-latitudes predominantly in a west–east direction, reaching an average wind speed of 165 km/h. Using this combination of high wind speeds and reliable direction, hydrogen-filled airships or balloons could carry hydrogen with a lower fuel requirement and shorter travel time compared to conventional shipping. Jet streams at different altitudes in the atmosphere were used to identify the most appropriate circular routes for global airship travel. Round-the-world trips would take 16 days in the Northern Hemisphere and 14 in the Southern Hemisphere. Hydrogen transport via the jet stream, due to its lower energy consumption and shorter cargo delivery time, access to cities far from the coast, could be a competitive alternative to maritime shipping and liquefied hydrogen tankers in the development of a sustainable future hydrogen economy.

## 1. Introduction

The transport sector was responsible for 23% of the total anthropogenic CO<sub>2</sub> emissions in 2013 [1]. From these, 3% of the emissions came from conventional ships in 2012 and CO<sub>2</sub> emissions are expected to increase by 50% to 250% from 2012 to 2050 [2,3]. There are several alternatives for reducing the emissions from shipping industry, such as lower the speed of the ships, use wind power [4–6], improve overall logistics and switch fuel to hydrogen produced with renewable energies [7].

In recent years, the requirement to reduce energy consumption and CO<sub>2</sub> emissions has increased researchers' and investors' consideration of airships as an alternative to maritime transport. Airships were introduced in the first half of the 20th century before conventional aircraft were used for the long-range transport of cargo and passengers [8]. However, their use in cargo and passenger transport was discontinued for several reasons, for example, the risks of a hydrogen explosion, [9,10] their lower speed compared with airplanes, the lack of weather forecasts at the time of deployment [11], and increased availability of cheap petroleum fuels, which reduced the costs of

conventional air transport and offered a convenient, faster, and safer alternative for long-range transportation.

Given the need to achieve the 1.5 °C warming target set out in the Paris Agreement and the expected growth in maritime shipping, the airship has been receiving increasing attention, as new materials have become available and significant improvements have been made to weather forecasting. Airships have been used or proposed for military uses [12], broadband services [13], as high-altitude platforms for investigating other planetary bodies [14], for surveillance and photography [15–17], for stratospheric tourism [18], competitive racing [19], advertising [20], and to release particles into the stratosphere to reduce incoming solar radiation [21]. Another major area of research and investment is using the airship for cargo transportation [22], such as delivery of food [23] and humanitarian aid [24].

Several research on airship are currently underway. For instance, the development of new designs [25,26], analysis of the dynamics of operation of airships [27–32], ascension to the stratosphere using wing energy [33], the impact of thermal variations in the ascent and descent trajectories [34,35], analyses of new materials for the construction of airships [36–38], such as aerogel [39], proposal of alternative

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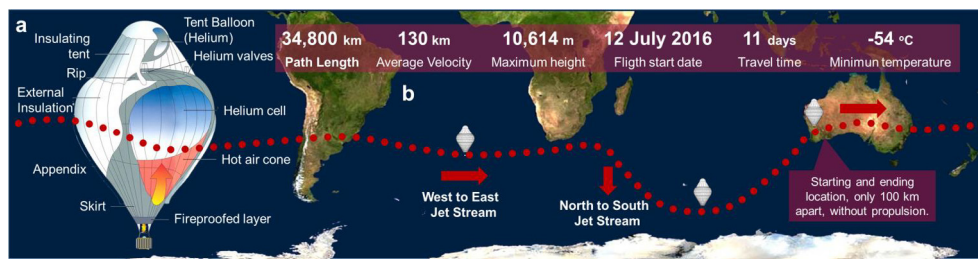


Fig. 1. Latest ballooning round-the-world record [66].

propulsion systems [40], reduce drag with shape optimization [41,42], experimental investigations [43], high altitude airship pressurization and air conditioning [44] have been recently published. Additionally, airships have been considered to be designed to be unmanned to reduce risks of fatalities, especially if the airship uses hydrogen for buoyancy [45].

Energy related studies have also been developed focusing on solar powered airships [46–54], renewable energies powered airships [55–57], hydrogen powered airships [50], high altitude wind power generation with airships [58–60], solar turbine power stations with floating solar chimneys [61], energy storage alternatives for airships with regenerative fuel cell (RFC) [62,63] and the effect of high-altitude on its energy system performance [64]. Other studies have also looked at the selection of the best airship routes with the intention for reducing fuel consumption assuming previously selected destinations [11,45].

Airships flying in the jet stream could reduce CO<sub>2</sub> emissions and fuel consumption for hydrogen and cargo transportation, as the jet stream itself would contribute to most of the energy required to move the airship between destinations. One example of using the jet stream for high speed transportation is balloon racing (Fig. 1) [66]. In the latest ballooning round-the-world record, a Roziere balloon has been used, which consists of combined buoyancy from helium gas and increase in temperature by burning propane (Fig. 1 (a)). Propane is used to vary the balloon's altitude to attain appropriate wind speed and direction to reach the final destination in the shortest time. The global circumnavigation record by balloon of 11 days was set in 2016 by the Russian, Fedor Konyukhov, in the Southern Hemisphere. The balloon's latitude varied from  $-27$  to  $-60^\circ$  (Fig. 1 (b)).

This paper evaluates the best routes to use the jet stream to push airships for the creation of a future, clean and sustainable cargo and hydrogen long-range transport sector. The paper is divided into five sections. Section 2 presents the issues and advantages related with using hydrogen in airships. Section 3 presents the methodology adopted in finding the optimal routes for airships pushed by the jet stream. Section 4 presents the results of this paper, which include the travel time from one city to another with airships in the northern and southern hemispheres. Section 5 discusses important issues involving airships and jet streams. Section 6 concludes the paper.

## 2. Transporting hydrogen in an airship

Airships can be filled with helium to create enough buoyancy for the airship to stabilize at heights of 10–20 km (thereby avoiding airplane flight paths for most of the journey). Although there could be a large demand for airship transportation, the high cost of helium would reduce commercial viability, especially in comparison with hydrogen which is cheap and abundant [67–69], however, using hydrogen poses a larger risk [70], as it is flammable and explosive, as seen in the 1937 Hindenburg disaster, which is the main reason why the use of airships was discontinued [71]. Around 90% of the reported accidents linked to hydrogen airships involved fire and the majority involved fatalities [72]. The risk of fatalities with hydrogen airships would, however, reduce considerably if (i) airship transportation, loading, and unloading were performed autonomously [65], (ii) airship ports were located in

isolated areas, and (iii) airships were not allowed to pass above large cities at low altitudes.

Hydrogen is a good energy carrier and a valuable energy storage alternative, having a gravimetric energy density (120 MJ/kg) three times higher than that of gasoline [73]. Given that renewable electricity, for example, excess wind power, can be transformed into hydrogen through the electrolysis of water, there is optimism that the hydrogen economy will form a fundamental part of a clean and sustainable future [74]. The most promising progress to date has been in the vehicle transport sector of Japan [75], with more than 100 hydrogen filling stations in existence as of 2018. The challenges of implementing a hydrogen-based economy involve cooling to below  $-253^\circ\text{C}$  in order to liquefy the hydrogen, a process that consumes approximately 30% of the embodied energy [76], with further energy of around 3% required to transport the liquefied hydrogen [77]. The energy consumed and costs involved in hydrogen liquefaction significantly hinder the viability of a hydrogen-based economy.

However, hydrogen could be transported in large airships or balloons filled with hydrogen. Instead of using energy in liquefaction, hydrogen in gaseous form could be carried inside the airship or balloon and transported by the jet stream with a lower fuel requirement. Once the airship or balloon reaches its destination, the cargo is unloaded and around 60% or 80% of the hydrogen used for lift is removed, leaving 40% or 20%, respectively, of the hydrogen inside the airship or balloon to provide enough buoyancy for the return trip without cargo. This assumes that the weight of the airship without cargo and hydrogen is around 40% or 20% of the weight of the airship or balloon with cargo and without hydrogen. In the Hindenburg, around 30% of the weight was represented by cargo and 70% by the airship itself. This reduction in airship and balloon weight is due to advances in materials engineering and gains with scale, especially with the reduced envelope (surface area) requirements.

The energy consumption for transporting hydrogen with airships or balloons is mainly related to the energy required to pressurize the hydrogen to reduce the vehicle's altitude or to return to the ground. This comprises of around 12% of the energy carried in the hydrogen. Assuming that the hydrogen is stored in tanks with a total pressure of 25 bar, the average compression energy is 1.7 kWh<sub>e</sub>/kg of H<sub>2</sub> [78], the energy used to pressurize the hydrogen comes from fuel cells that are 70% efficient, 30% of the energy from decompression is stored and reused. Ninety percent of the hydrogen in the airship or balloon has to be pressurized twice (once full, during delivery, and once empty, in the return flight) to reach the ground, and a similar amount of energy is required to gain or lose altitude to fly at the most appropriate wind speeds. Note that part of this energy requirement could be generated using solar arrays on the top of the airship or balloon. The energy consumption is around three times lower than that of liquefied hydrogen tankers. Another advantage of airships over liquefied hydrogen tankers is that they also carry cargo and have a shorter delivery time.

To date, the largest airships ever constructed were the Hindenburg class airships developed in the 1930s [72,79], which allowed for a crew of 40 people, 72 passengers, had a length of 245 m, diameter of 41 m, volume of 200,000 m<sup>3</sup>, and a useful lift of 10 tons. The envelope area and hydrogen or helium gas volume ratio reduce considerably with the

**Table 1**  
Changes in dimensions, volume, surface area and useful lift.

Description	Hindenburg class	Airship hydrogen carrier	Balloon hydrogen carrier*	
			Stratosphere	Sea level
<b>Type</b>	Rigid		Non-rigid	
<b>Dimensions</b>				
Dimensional increase	× 1	× 10	× 2.97	× 1.58
Length (m)	245	2453	727	386
Diameter (m)	41.2	412	727	386
<b>Volume</b>				
Volume ratio	× 1	× 1000	× 1000	× 1000
Hydrogen Volume (km <sup>3</sup> )	0.0002	0.2	0.2	0.03
<b>Surface Area</b>				
Envelope ratio	× 1	× 100	× 75.2	
Envelope (km <sup>2</sup> )	0.022	2.207	1.660	
<b>Weight</b>				
Cargo useful lift (tons)	10	21,000	28,000	
Empty weight (tons)	25	14,000	7000	
Total weight (tons)	35	35,000	35,000	
Cargo weight share (%)	28	60	80	
Hydrogen weight (tons)	3.3	3280	3280	
Hydrogen delivery (tons)	0.9	1968	2624	
<b>Services</b>				
Energy storage (GWh)	0.1	100	100	
Energy delivery (GWh)	0.03	60	80	
Deliveries per year	20–25	20–25	20–25	
Delivery & return (days)	15–20	15–20	15–20	
<b>Other</b>				
Assumed maximum operational height (km)	15	15	15	

increase in airship dimensions. For example, while a tenfold increase in the diameter and length of the airship will increase the hydrogen volume stored and its useful lift a thousand-fold, it will only increase the envelope material by a factor of 100. This means that the cost of the envelope of the airship reduces tenfold (Table 1).

Table 1 shows the changes in dimensions, volume, envelope area, and useful lift of airships and balloons. An airship 10 times longer than the Hindenburg class airship or a balloon on the ground that is 60% longer than the Hindenburg class airship would be able to transport 0.2 km<sup>3</sup> of hydrogen, which is equivalent to 3280 tons of hydrogen, assuming a minimum pressure in the airship or balloon of 150 hPa, at 15 km height, a temperature of -50 °C (average temperature at the stratosphere), and a density of 0.0164 kg/m<sup>3</sup>. The largest LNG tanker (Mozah) has a 128,900 deadweight tonnage. Assuming 25 deliveries around the world per year, 1125 of these airships would be able to transport energy equivalent to 10% of current world electricity consumption.

Fig. 2 presents a size comparison between the largest solar power plant, the Hindenburg class airship, the hydrogen carrier airship, and the hydrogen carrier balloon. One hydrogen carrier airship or balloon with an energy storage of 0.1 TWh, can deliver all the energy produced by the Tengger Desert Solar Park (solar power plant) in China, which has a 1547 MW electricity generation capacity, assuming 25 airship deliveries per year and that 80% of the hydrogen is delivered.

Docking airships is challenging due to their large size, limited

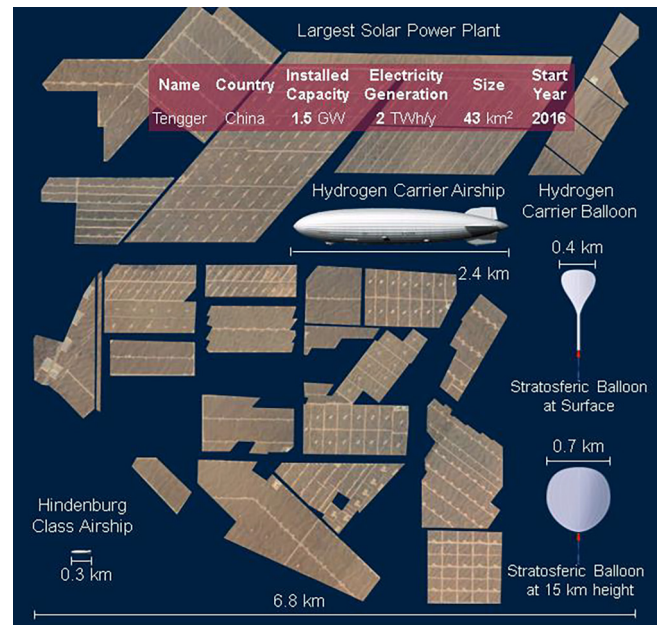


Fig. 2. Hydrogen airship and balloon characteristics.

control mechanisms, and high wind drag. Another particular issue is to keep the airship attached to the ground during windy episodes. The diameter of the airship hydrogen carrier (Fig. 2) is similar to the height of the Empire State Building in New York. It would be very challenging to keep such large airship from collapsing under strong superficial winds. On the other hand, balloon hydrogen carriers are not rigid and vary in size. Their volume on the ground is around seven times smaller than in the stratosphere (assuming a maximum operation height of 15 km). This is convenient because the size of the balloon hydrogen carrier on the ground is only 58% larger than the Hindenburg class airship, and the balloon can be deflated in the event of strong winds; balloons should thus be the most viable and practical solution for transporting large amounts of hydrogen. Another benefit of the balloon being non-rigid is that it is lighter, which allows it to deliver more hydrogen per trip.

### 3. Methodology

The jet stream is caused by the difference in temperature between the poles and mid-latitudes, which results in warmer air flowing into the poles in high altitudes. This happens due to the Polar cycle atmospheric circulation, where air descends in the poles (because it is colder) and ascends in the mid-latitudes (because it is warmer). This is combined with the rotation of the Earth, that is, the Coriolis effect, which diverts the wind to the left in the Northern Hemisphere and to the right in the Southern Hemisphere (i.e., in a west-east direction). A good approach to the analysis of the behavior of the jet stream at different pressure levels is to use the *Windy* website [80], select wind speed, pressure level of 150 hPa, then zoom out to see the whole world. The data from *Windy* are taken from the ECMWF [81] or Global Forecast System (GFS) [82].

The main parameters analyzed in this paper are wind speeds at jet stream altitudes and how these can be used to transport hydrogen and cargo from one place to another. The wind speed data analyzed are the Pressure Levels Reanalysis ERA5 data from European Centre for Medium-Range Weather Forecasts (ECMWF) [81]. The wind speed is divided into two components, the west to east (W-E) wind speeds and the north to south (N-S) wind speeds. The W-E wind speeds are represented by a positive value, for example, from Buenos Aires to Cape Town. The east to west wind speeds are represented by a negative sign,

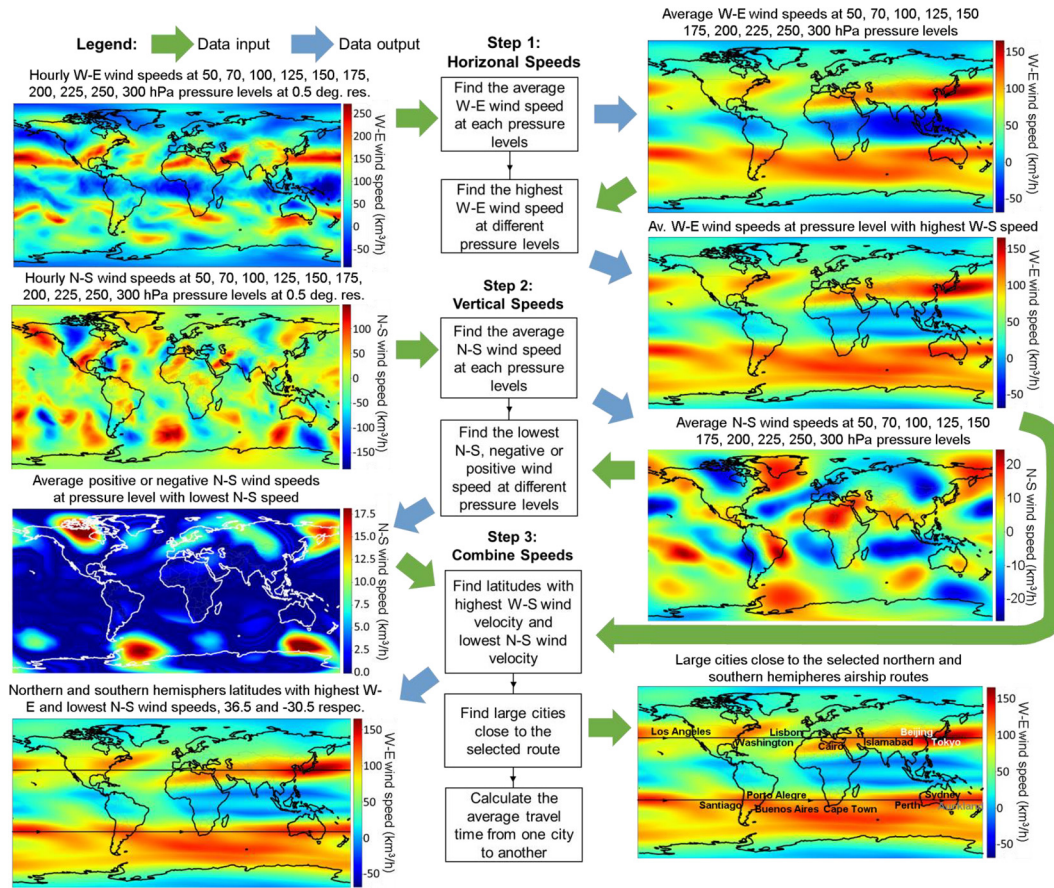


Fig. 3. Jet stream airship world potential model framework.

for example, from London to New York. The south to north N–S speeds are represented by a positive sign, for example, from Hong Kong to Shanghai, and north to south N–S speeds are represented by a negative sign, for example, from Germany to Italy.

Fig. 3 presents the Jet Stream World Potential Model Framework. It is divided into three steps. Step 1 consists of input hourly W–E wind speed data at 50–300 hPa pressure levels (or height above the ground) at a 0.5° resolution. The average wind speeds for all the different pressure levels are then plotted. Given that the airship can change altitude and pressure levels to travel in faster wind speeds, the pressure levels with the highest wind speeds are selected. This results in the highest average W–E wind speed map. Step 2 consists of inputting hourly N–S wind speed data at 50–300 hPa pressure levels at a 0.5° resolution. The average N–S wind speeds for all the different pressure levels are then plotted. Similar to Step 1, the airship can move to the pressure level with the lowest N–S wind speed to maintain its route. By combining the average N–S wind velocities with the minimum N–S speeds, the lowest average positive or negative wind speed map is created. Step 3 consists of finding the ideal latitude for the airship in the northern and southern hemispheres with Eqs. (1)–(3). The largest cities close to these ideal latitudes, which might benefit from an airship route, are then selected. Thereafter, the highest average W–E wind speeds map is used to estimate the travel time from one city to another using only the jet stream and assuming that the N–S winds will not affect the route of the airship.

To estimate the time for the airship to travel between different cities, we assume the velocity of the airship to be 90% of the velocity of the jet stream [83] and that the average jet stream wind speeds are constant. It is important to note that the distance traveled by the airship is not the shortest distance from one city to another, which assumes the same latitude throughout the route. This is because of the predominant

wind patterns are W–E, and if the airship reaches too far down, the W–E will reduce and the airship might not be able to return to the ideal speed latitude.

Equation (1) was used to determine the airship jet stream latitude potential, which indicates how appropriate a latitude is for airship jet stream transportation. The higher the average W–E velocity and the lower the N–S velocity, the higher the airship jet stream potential.

$$LP_{lat} = \sum_{lon=-180}^{180} HV_{lat,lon} - \sum_{lon=-180}^{180} VV_{lat,lon} \quad (1)$$

where

- $LP$  is the airship jet stream latitude potential at latitude  $lat$ .
- $lat$  is the latitude under analysis.
- $lon$  is the longitude under analysis.
- $HV_{lat,lon}$  is the average, W–E, wind speeds at the pressure level with the highest speed, at latitude  $lat$  and longitude  $log$ .
- $VV_{lat,lon}$  is positive, average, W–E, wind speeds in the pressure level with the lowest speed, at latitude  $lat$  and longitude  $log$ .

Equations (2) and (3) are then used to find the optimal latitude for the northern and southern hemisphere airship routes, respectively. The maximum airship jet stream potential latitude in the northern and southern hemispheres were found to be 36.5 and  $-30.5^\circ$ , respectively.

$$SL_N = \max(LP_{lat}) \text{ if } lat > 0 \quad (2)$$

$$SL_S = \max(LP_{lat}) \text{ if } lat < 0 \quad (3)$$

where

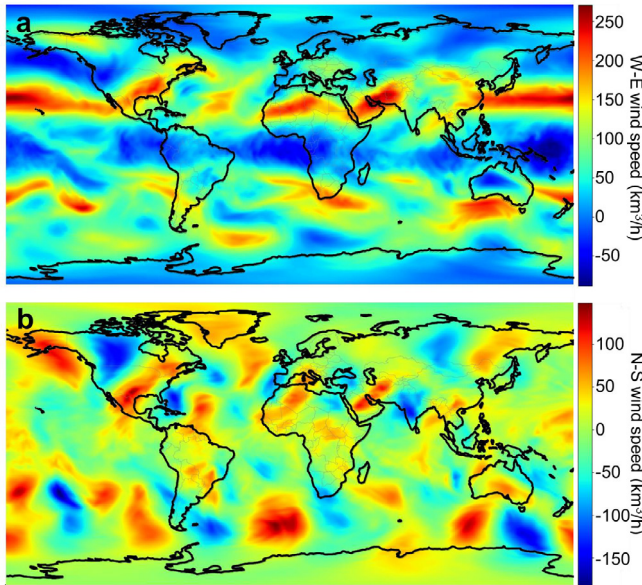


Fig. 4. Jet stream (a) W-E and (b) N-S wind speeds at 225 hPa pressure level (01, April 2016 00 pm).

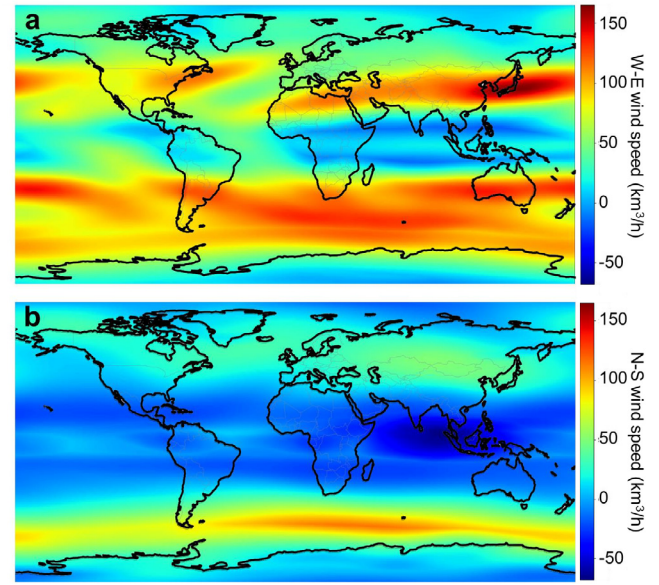


Fig. 5. Average W-E wind speeds considering the (a) maximum and (b) minimum W-E speed at all pressure levels from 2016 to 2017.

$SL_N$  is the maximum airship jet stream potential latitude in the Northern Hemisphere  
 $SL_S$  is the maximum airship jet stream potential latitude in the Southern Hemisphere

#### 4. Results

This section presents the results from the jet stream airship world potential model framework.

##### 4.1. Wind data processing

The primary data from this study is the hourly average wind speed at different pressure levels taken from the Pressure Levels Reanalysis ERA5 data from European Centre for Medium-Range Weather Forecasts (ECMWF) [81]. These are divided into two components, the west to east (W-E) wind speeds (Fig. 4 (a)) and the north to south (N-S) wind speeds (Fig. 4 (a)).

To find the average wind speeds and average travel times from one location to another, the average wind speeds from 2016 and 2017 at pressure levels of 50, 70, 100, 150, 175, 200, 225, 250, 300 hPa were considered. The inclusion of several pressure levels in the analysis allows the airship operator to gain or lose altitude to find the pressure level with the most appropriate wind speeds to reach the final destination with the lowest energy consumption and shortest time (Fig. 5). The W-E wind speeds at latitudes between the tropics and the polar circles are strong and predominantly positive, namely, from west to east. The wind at the equator and within the polar circles is weak and predominantly negative, namely, from east to west. This pattern continues during most of the year. However, it should be noted in Fig. 5 (b) that the minimum speeds at the Southern hemisphere are considerably higher than in the Northern hemisphere. This benefits the use of Airships in the Southern hemisphere, as it reduces the chances that the airship will be stuck in a certain location due to low wind speeds.

Table 2 presents some characteristics of the jet stream at different pressure levels. The pressure levels with the highest average W-E wind speed (165 m/s) is 200 hPa, which is equivalent to an altitude of 12 km. This is also the altitude with the lowest average of N-S wind speeds (22.09 m/s), which is convenient as it would reduce the chances that the airship is blown away from its original latitude route.

Fig. 6 presents the minimum average latitudinal wind speeds

considering all pressure levels. The negative wind speeds (N-S) were turned into positive (S-N) with the intention of finding the route with the least disruption to the airship's latitude. The optimized travel of the airship is to use the predominant positive longitudinal wind speeds (W-E), avoiding latitudinal wind speeds as much as possible to prevent the airship being blown off its set route. Fig. 6 shows locations where the minimum average N-S wind speeds are equal to zero (dark blue lines) and locations with predominantly positive or negative average wind speeds (red patches), which should be avoided by airships. As it can be seen, the regions ranging from around 40° and -45° latitude do not have predominant north or south winds, and could appropriately use the jet stream for circumnavigation transportation as proposed in this paper.

Although seasonal variations were not included in this paper's analysis, they have considerable impact on transport time when compared with the yearly average. To highlight the impacts of seasonal variations on the W-E wind speeds, Fig. 7 presents the average W-E wind speeds of the highest and lowest speed pressure levels in the winter and summer in the Northern Hemisphere. This shows that the W-E wind speeds in the Northern Hemisphere are stronger during the summer in the Northern Hemisphere and that the W-E wind speeds are stronger during summer in the Southern Hemisphere. It can also be seen that the lowest W-E average wind speeds in the Southern Hemisphere are higher than in the Northern Hemisphere, particularly during summer in the Southern Hemisphere. This reduces the chances of the airship moving at low speeds.

##### 4.2. Finding the ideal latitude routes

The ideal latitude routes in the Northern and Southern hemisphere are presented in Fig. 8. They are a result of Eqs. (1)–(3). It was found that the ideal latitude in the northern hemisphere is 36.5° and in the Southern hemisphere is -30.5°. It can also be seen in the graph in Fig. 8 that the Southern hemisphere has a much wider range of latitudes which would be interesting to develop airship routes. However, the Southern Hemisphere has considerably less land and cities to be connected when comparing to the Northern hemisphere.

##### 4.3. Travel time from city to city

Table 3 presents the distance and travel time from the cities selected

**Table 2**  
Jet stream characteristics at different pressure levels.

Pressure levels (hPa)	Altitude (km)	Maximum W-E wind speed (km/h)	Average W-E wind speed (km/h)	Minimum W-E wind speed (km/h)	Average W-E wind speed (km/h)	Maximum N-S wind speed (km/h)	Average N-S wind speed (km/h)	Minimum N-S wind speed (km/h)	Average N-S wind speed (km/h)
50	20.481	351.66	121.76	-221.08	-25.64	268.15	39.21	-260.65	-25.55
70	18.442	334.87	116.94	-178.96	-31.47	232.07	33.34	-227.80	-23.98
100	16.180	305.38	115.26	-211.57	-54.59	207.52	27.04	-207.92	-22.73
125	14.765	323.97	133.16	-229.77	-67.47	201.23	23.47	-223.27	-22.22
150	13.609	361.60	153.05	-208.33	-63.51	244.33	23.40	-297.14	-24.88
175	12.631	428.68	161.10	-227.55	-43.26	378.87	24.89	-360.91	-29.17
200	11.784	407.08	164.90	-217.43	-48.48	331.88	22.09	-369.89	-26.95
225	11.037	401.43	162.81	-188.60	-54.94	307.05	24.60	-350.40	-26.51
250	10.363	433.81	154.26	-242.20	-38.21	371.74	27.86	-356.38	-30.44
300	9.164	421.24	137.50	-243.88	-31.39	345.87	32.39	-320.87	-30.24
All	-	433.81	164.90	-243.88	-67.50	378.87	39.21	-369.89	-30.44

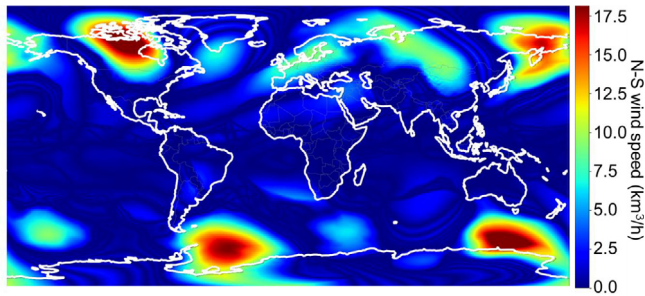


Fig. 6. Average positive N-S wind speeds considering the minimum N-S speed at all pressure levels from 2016 to 2017.

in Fig. 3. Assuming the ideal latitudes found in the previous section, the round trip time route in the northern hemisphere takes 16 days at 36.5° latitude, and in the southern hemisphere takes 14 days at -30.5° latitude. This delivery time is considerably smaller when compared with maritime shipping, particularly in the southern hemisphere. Note that this estimation does not take into account the time taken for the airship to rise to the stratosphere, lower to the ground, unloading and loading, security check and etc. It only takes into account the wind speeds at the stratosphere. Thus, if the airship is scheduled to stop in the cities presented in Table 3, the round trip travel time would take much longer.

### 5. Discussion

Given the high number of discussion points that require to be detailed, this section is divided into the subsections presented below:

#### 5.1. Unidirectional, west to east routes

Using the jet stream for airship and balloon transportation has some peculiarities. A major consideration is that the airship has to travel in one direction, from west to east, around the world. For example, an airship would fly from New York to London; however, the return trip would be very difficult. Another consideration is that, most of the energy requirement in airships and balloons is the lift to the stratosphere as the jet stream pushes them to their final destination, thus, long-distance routes should be prioritized.

#### 5.2. Competition with conventional planes long haul flights

Long haul flights cruising altitude for conventional planes can reach as high as 14 km of altitude. Given that the pressure levels with the highest average W-E wind speed (165 m/s) is 200 hPa, which is equivalent to an altitude of 12 km, airships and conventional planes will have to share the same altitude range of their flight routes if they want to better use the jet stream. The introduction of airships will then require new regulations to reduce the risks of accidents between planes and airships.

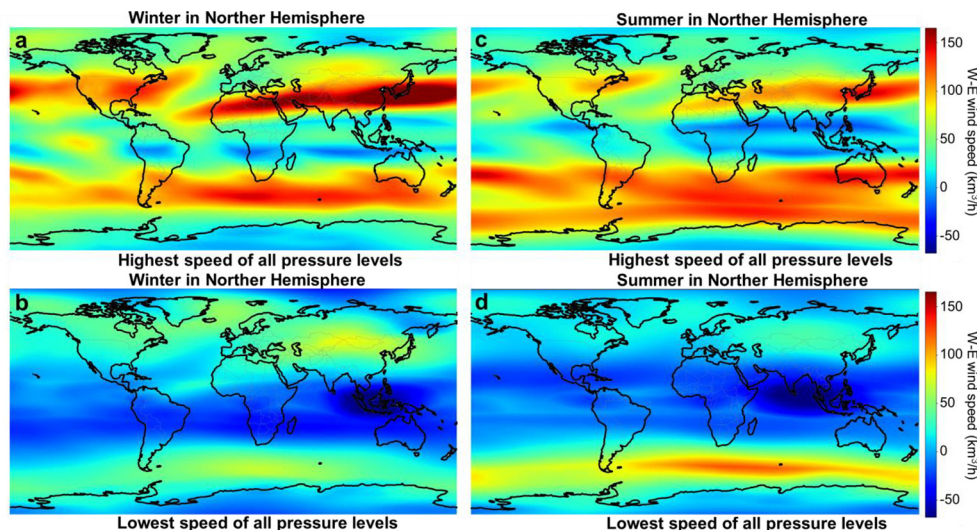


Fig. 7. Average W-E wind speeds at pressure levels with highest and lowest speeds in the winter and summer in the Northern Hemisphere.

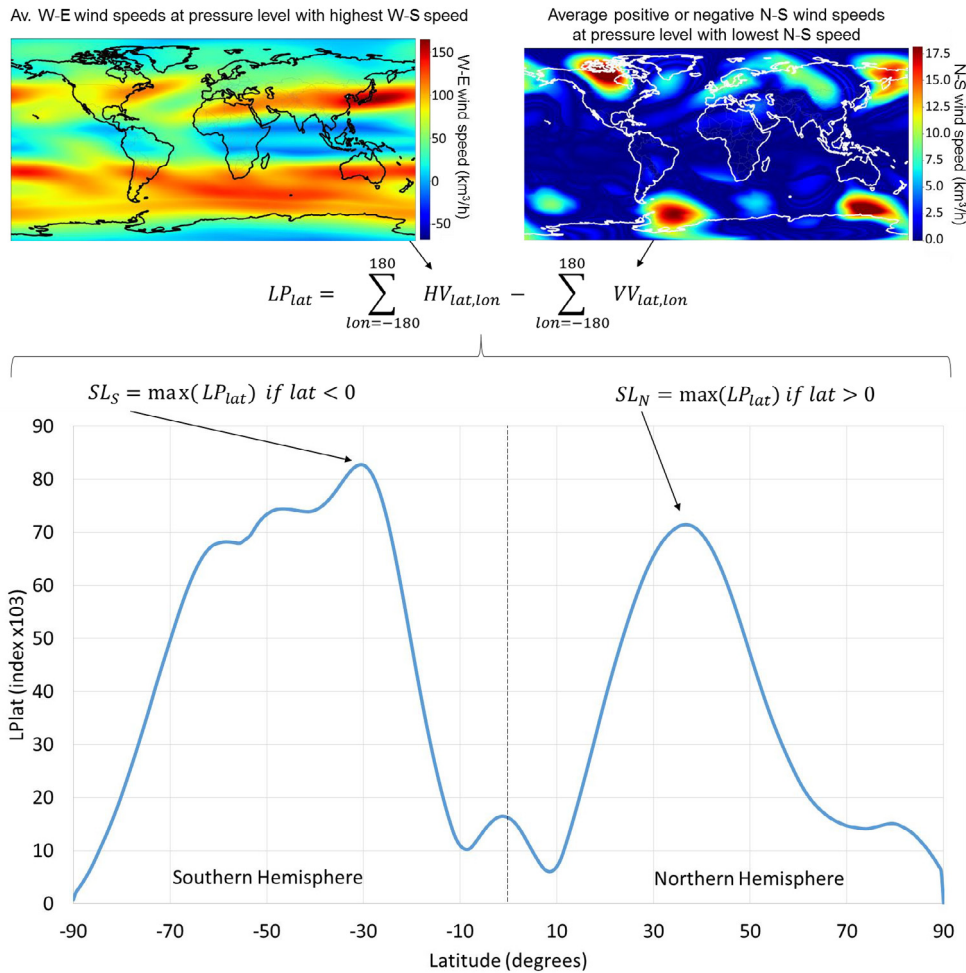


Fig. 8. Finding the Ideal Latitude Routes.

5.3. Wind drag

The airship design should have a variable drag, which should be as high as possible. However, the drag should be reduced as much as possible if the jet stream is pushing the airship away from its final destination. The drag could be varied using adjustable sails. It should be noted that a structure larger than, say, 1 km is extremely delicate. If

there is a considerable difference in the wind velocities between the front and the back of the airship, during a storm, it could be torn in half. Thus, it should be built to be strong enough to withstand the shear caused by the winds from different directions. New material technologies might be able to guarantee the robustness and resilience to endure heavy storms.

Table 3 Distance and travel time from city to city in the northern and southern hemisphere routes.

Initial city	Longitude of initial city	Final city	Longitude of final city	Distance (km)	Average wind speed (km/h)	Time (days)	Freight shipping (days) [84]
<i>Northern Hemisphere</i>							
Los Angeles	-118	Washington	-77	3673	89	1.9	8-10
Washington	-77	Lisbon	-9	6092	69	4.1	11-13
Lisbon	-9	Istanbul	30	3494	73	2.2	6-8
Cairo	30	Islamabad	73	3852	106	1.7	10-12
Islamabad	73	Beijing	116	3852	121	1.5	9-17
Beijing	116	Tokyo	140	2150	154	0.6	4-5
Tokyo	140	Los Angeles	-118	9138	113	4.0	18-22
Total	32,251	101	15.9	66-87			
<i>Southern Hemisphere</i>							
Santiago	-71	Buenos Aires	-58	1248	124	0.5	38-50
Buenos Aires	-58	Cape Town	18	7296	106	3.2	14-17
Cape Town	18	Perth	116	9408	114	3.8	18-22
Perth	116	Sydney	151	3360	134	1.2	39-47
Sydney	151	Auckland	175	2304	127	0.8	7-9
Auckland	175	Santiago	-71	10,943	116	4.4	20-27
Total	34,559	116	13.9	136-172			

#### 5.4. Energy supply

The airships proposed in this paper could have solar arrays installed. Batteries would allow the airship to generate and store energy for when the airship needs to fly in a direction different from the jet stream's direction, and the stored energy could be used to operate motors to maintain the airship on its original route. Alternatively, some of the hydrogen stored in the airship could be used for propulsion.

#### 5.5. Energy consumption

Even though the jet stream is used to push the airship to its final destination, a lot of energy is involved to lift the airship to a 15 km altitude and to bring it back to the ground. This paper assumes that the energy consumption of airships is four times higher than in maritime shipping. This assumes that 30% of the energy released while the hydrogen gas is depressurized during the lift is stored and used to compress the hydrogen during descent. The energy consumption would considerably reduce if more energy generated is recovered. Assuming that all the energy released during the lift is reused during descent and the jet stream blows the airship to its final direction, the energy consumption of the airship would be zero.

#### 5.6. Cost estimation

This paper proposes that airships and balloons should carry either cargo or hydrogen or both. This market flexibility would increase the viability of the technology. For example, if an airship lands full of cargo, there is no cargo available for the return trip, and the cost of energy at the destination is high, the hydrogen from the airship can be sold to the energy market and the airship can return with less hydrogen and no cargo. Compare, for instance, the cost of transporting 21,000 tons of cargo from Denver (USA) to Islamabad (Pakistan) (USD10,500,000, assuming a cost of 500 USD/ton) with the cost of transporting 60 GWh of hydrogen energy (USD 2,400,000, assuming a cost of 40 USD/MWh). Airships and balloons could be a viable alternative for cargo and hydrogen transportation, giving preference to cargo transportation between cities far from the coast. Cargo needing to be kept frozen or at low temperatures also benefits, given that stratospheric temperatures average 60 °C.

#### 5.7. Global warming impact on airships

Future work involves running the methodology proposed in this paper with data from different Global Climate Models to look at the impact of global warming to this type of transportation in a future paper. Global warming impacts to airships might include the increase in frequency of extreme weather events, such as hurricanes and storms, which directly impacts the effectiveness of airships. Also the increase in temperature in the Arctic regions, will reduce the temperature difference between the Arctic Circle and the mid-latitudes, which would weaken the Northern Hemisphere jet stream.

#### 5.8. Cooling services

Once the airship arrives at its final destination, the hydrogen used for buoyancy will be pressurized and will be at a temperature of around  $-60$  °C, which is the average temperature of the stratosphere. We assume that the airship is carrying 3280 tons of hydrogen, has a specific heat of 14.4 KJ/kg.C, a temperature difference of 70°, no losses occur, and that the heat is extracted in one day. The hydrogen could be used as a cooling sink with a cooling power of 30 MW (equivalent to cooling a large airport or resort in a tropical location). This could be used to run district cooling services or industrial processes such as natural gas liquefaction or liquid air production.

#### 5.9. Hydrogen liquefaction

During the process of lowering the airship to the ground, some of the hydrogen in the airship could be used to liquefy hydrogen. This is convenient because the airship would require less volume and dead weight in the airship to store the compacted hydrogen. Another benefit is that stratospheric temperatures are as low as  $-70$  °C, which would considerably increase the efficiency of hydrogen liquefaction. This liquid hydrogen could then be sold or used for cooling on its final destination.

#### 5.10. Artificial precipitation

Airships or balloons could also be used for rainmaking. Some of the hydrogen used to lift the airship could be used to generate electricity with fuel cell using the oxygen in the stratosphere for additional propulsion to drive the airship, or to liquefy hydrogen. One of the by-products from electricity generation with hydrogen is water. One ton of hydrogen produces nine tons of water. The water produced increases the weight on the airship and, thus, reduces the energy required to compress the hydrogen, when returning to the ground. This water could also be released from the stratosphere at a height in which the water will freeze before entering the troposphere where it would melt. Reducing the temperature of the troposphere would increase its relative humidity until it saturates and precipitation begins. The commencement of the precipitation would initiate a convection rain pattern, feeding more humidity and rain into the system.

#### 5.11. Space launch

Airships could be used to carry space supplies to the stratosphere, from where they could be expelled into space using a pressure gun. Alternatively, a donut shaped airship could support a spaceship on its center of gravity, from where it would launch into space. This would allow the spaceship to be built with a higher volume to area ratio due to the reduced losses caused by friction. This technology could be used to supply the international space station or to reduce the costs for the manned missions to Mars by various space agencies.

Table 4 presents a summary of the advantages and disadvantages of airships and balloons.

### 6. Conclusion

This paper presented an innovative alternative for transporting cargo and hydrogen using the jet stream as the main source of energy to push an airship or balloon to its final destination. It was found that the round trip in the northern hemisphere at a latitude of  $36.5^\circ$  takes 16 days and the round trip in the southern hemisphere at a latitude of  $-30.5^\circ$  takes 14 days. This is considerably faster than maritime shipping alternatives.

This paper has pointed out several benefits and challenges for transporting cargo and hydrogen with airships. Airships and balloons have the advantage of reaching locations with difficult access in the middle of the continent. This could reduce the cost of transportation of goods produced by or delivered to cities far from the coast. Countries that do not have access to the ocean would also benefit from airships, as they would not have to rely on intermediary countries. Hydrogen transportation in airships has the benefit of not requiring to liquefy hydrogen, which requires a lot of energy. A main challenge is the need to reduce energy costs involved in pressurizing the hydrogen to lower the airship to the ground. These costs could reduce with an efficient alternative for storing the energy released when rising the airship. Another alternative is to produce water with the hydrogen, while generating energy in the airship, which would increase the weight of the airship and help lowering it to the ground. Other challenges involve the risk of explosion, damages with storms and grounding the airship



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

Advantages	Disadvantages
Energy can be generated using solar arrays or using 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 planes long haul flights will share the same altitude, which could contribute to accidents between airship 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 has the potential of destroying 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 in airship is estimated to be four time higher than in maritime shipping.
The water produced increases the weight on the airship and, thus, reduces the energy required to compress the hydrogen, when returning to the ground.	
Airships can be used to facilitate the launch of objects to space.	

during windy events.

It is estimated that 1125 airship hydrogen carriers would be able to transport energy equivalent to 10% of current world electricity consumption. The possibility of cheap and clean transportation of hydrogen would be convenient for the implementation of a global hydrogen economy. This would ultimately support the widespread adoption of intermittent renewable energy technologies, such as solar and wind, and promote sustainable development on a global scale.

#### 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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