Harnessing Off-Grid Renewable Energy

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***Abstract*—This paper explores how to economically harness renewable energy resources that are off-grid or otherwise isolated from customers. Its hypothesis is that under certain conditions, isolated renewable energy resources can be economically harnessed by using unmanned hydrogen-filled airships. Because hydrogen is an energy carrier and a lifting gas, unmanned hydrogen-filled airships can be used to carry hydrogen and cargo simultaneously. Unmanned airships do not have air crews to be put at risk although hydrogen airship safety has been reportedly increased. Furthermore, unmanned airships reduce cost in personnel. Finally, this paper proposes an operational model of hydrogen airships for efficient delivery of hydrogen within a known multiplier of optimum.**

Keywords—Air Transportation; Energy Harvesting; Energy Resources; Hydrogen Storage; Intelligent Vehicles; Optimal Scheduling

I. MOTIVATION

Harnessing renewable energy resources is important because those resources may eventually become scarce. Scarcity could increase energy prices. Increased energy prices, in turn, could increase hardship, especially the hardship of those who might have difficulty absorbing higher energy prices.

A key to economically harnessing renewable energy resources is transportation. An important transportation-related quality of hydrogen is that hydrogen is a lifting gas for airships. Hydrogen as a lifting gas has been the subject of recent research (referenced in Section III-A below).

Cargo-carrying airships (e.g., Fig. 1 [14]) were the theme of a workshop where Alaskans demonstrated substantial interest in the idea of cargo airships linking vendors and customers to remote sites [9, p. 2]. The combination of cargo airship developments and hydrogen production advances has the potential to deliver isolated renewable energy resources economically.

Hydrogen is valuable not only as an energy carrier, but as a reactive element. To combine a molecule with hydrogen is to *hydrogenate* that molecule. For example, hydrogenation of carbon dioxide yields heat, methane, and water by the well-known Sabatier reaction. Methane is the large majority of *natural gas*. Because an extensive natural gas infrastructure already exists, converting carbon dioxide and renewable-energy-produced hydrogen into methane and water may be an effective way to deliver and store renewable energy.

II. CONTRIBUTIONS

Motivated by the need to harness renewable energy resources and by advances in hydrogen airships, this paper makes two key contributions:

Fig. 1: An airship that can carry cargo. Courtesy Lockheed Martin Corporation. Used by permission. All rights reserved.

- A framework to harness energy from isolated renewable energy resources by using hydrogen's energy-carrying capacity and lifting power (Section III), and
- A mapping of this airship application to an existing heuristic to schedule each hydrogen-filled airship in a fleet to add optimum value or within a pre-determined factor of optimum value. E.g., the heuristic suggests whether an airship should transport cargo, compress its lifting gas, and/or load pre-compressed lifting gas (Section IV).

III. HYDROGEN IS AN ENERGY CARRIER AND A LIFTING GAS

Hydrogen is an energy carrier. It can be used to store and to transport energy to energy customers. Energy customers are able to extract energy from hydrogen using various devices (e.g., fuel cells and internal combustion engines).

Hydrogen can be produced from either fresh or seawater [12]. Sites that are ideal for our proposed energy harnessing system have water, wind, and products nearby to export, but no pipeline or grid connections.

Linking isolated (i.e., off-grid) renewable energy sites with grid-connected power plants is described in U.S. Patent 7 911 071 [6]. That patent claims a system in which wind farms convert sea water to hydrogen, which is then transported to hydrogen-burning electrical power plants. That disclosure suggests an embodiment that uses compressed-gas-carrying marine ships.

That system negates the lifting power of hydrogen by compressing it. Alternatively, let us consider hydrogen's value as a lifting gas.

A. *Safety*

Hydrogen was used extensively as a lifting gas before the Hindenburg disaster. A study has concluded that the cause of the Hindenburg's fire was not its hydrogen lifting gas, but the Hindenburg's skin [2]. Nevertheless, at least one design allegedly presents a safer hydrogen airship architecture. The work "Fire-safe Airship System Design" is described as presenting an airship design that prevents hydrogen from reaching dangerous concentrations in the main balloon. That design features "a multi-balloon structure with a naturally ventilated shape" [19]. Because natural ventilation is a passive system, that aspect of the design, which also includes an active system, seems very promising. It is interesting to point out that similar to our work, the airship in that design stores energy in hydrogen, but as opposed to our work, it compresses it to be later used for airship propulsion. In our work we primarily use uncompressed hydrogen to transport energy and our goal is to economically deliver it.

To further reduce chances of injury, hydrogen airships can be unmanned. By-definition, unmanned airships are crewless. Crewless hydrogen airships obviously do not put their non-existent flight crews at risk. Unmanned airships are available today to fly over-the-horizon tasks [11]. For long endurance tasks, a major aerospace organization has tested an unmanned airship that is solar powered [15]. Another major aerospace organization is currently examining the potential of unmanned airships for delivering commercial freight [18].

B. *Determining Excess Lifting Gas of an Airship*

Excess lifting gas here is lifting gas that an airship needs only to lift its payload or cargo. If that cargo capacity (mass) is known and what lifting gas that airship uses is known, then the following equation can be used to determine the mass of that airship's excess lifting gas:

$$excess\_lifting\_gas\_mass = \frac{airship\_lifting\_capacity\_mass}{|gas\_lifting\_power|} \times gas\_density. \quad (1)$$

Let us use Equation (1) to determine the amount of excess lifting gas of the conceptual semi-rigid CargoLifter CL 160. The CargoLifter CL 160 is designed to hold 450 000 m^3 (15 891 600 ft^3) of helium lifting gas and to lift cargoes of up to 160 metric tons [5]. Since the lifting power of helium is about 98% of the lifting power of hydrogen [13, p. B-20], let us assume that the lifting powers of helium and hydrogen are the same and that the CL 160's lifting gas is hydrogen. The lifting power of hydrogen (H_2) is about -1.2 kg/m^3 (-0.076 lb/ft^3) at standard temperature and pressure (STP), which is 0°C (32°F), 101.325 kPa (760 mm) [13, p. B-20]. The density of hydrogen at normal temperature and pressure (20°C (68°F), 101.325 kPa) is 0.08375 kg/m^3 [10], which is less than hydrogen's density at STP. To be conservative, let us use the lower density. Now that we have all the physical constants on the right side of Equation (1), let us calculate the amount of the CL 160's excess lifting gas:

$$\begin{aligned} &excess\_lifting\_gas\_mass \\ &= \frac{airship\_lifting\_capacity\_mass}{|H_2\_lifting\_power|} \times H_2\_density \\ &= \frac{160\,000 \text{ kg}}{1.2 \text{ kg/m}^3} \times 0.08375 \text{ kg/m}^3 \approx 11\,000 \text{ kg of H}_2. \end{aligned}$$

C. *Significance of 11 000 kg of Excess Hydrogen Lifting Gas*

In the previous section (Section III-B), we calculated that the excess lifting gas of our theoretical hydrogen airship is approximately 11 000 kg. How does that amount compare to a goal for hydrogen tube trailer delivery capacity? And, for approximately how many years could that amount propel a hydrogen powered automobile?

1) Ten Times U.S. Department of Energy Goal: The U.S. Department of Energy has had this target for hydrogen tube trailer delivery capacity: 1 100 kg by FY2017 [3]. The FY2017 tube trailer delivery capacity goal is 10% of 11 000 kg. Thus, by delivering the excess gas in its lifting envelope, a hydrogen version of the conceptual CargoLifter CL 160 airship could theoretically exceed the FY2017 tube trailer delivery goal by ten times. Please note that the CL 160 is a very large airship. A half-scale version could surpass the goal by five times.

2) Forty-Eight Years' Worth of Fuel for a Hydrogen-Powered Automobile: Let us round 11 000 kg down to 10 000 kg to determine how many years that 10 000 kg of hydrogen could propel an automobile. The 2008 Honda FCX Clarity has a tank capacity of 3.75 kg and a 115.9 km/kg (72 mi/kg) mileage [1], which gives it a range of 434.6 km (270 mi). Thus, 10 000 kg of hydrogen can power the Clarity for 1 159 000 km (720 000 mi). If the Clarity were driven 24 140 km/year (15 000 mi/year), 10 000 kg of hydrogen would propel it for 48 years.

3) Forty-Nine Thousand Liters of Water and Over Thirteen Average Households' Annual Supply of Natural Gas: By the well-known Sabatier reaction

$$4\,H_2 + CO_2 \longrightarrow CH_4 + 2\,H_2O \quad (2)$$

mentioned above, 11 000 kg of hydrogen can be used to hydrogenate ∼60 000 kg of carbon dioxide (CO_2) to produce ∼49 000 liters of water (H_2O) and ∼1 200 gigajoules of methane (CH_4). (The details of that reaction are presented in the appendix.) That much methane is over thirteen times the average amount of natural gas used yearly by each Canadian household that uses natural gas (92 gigajoules) [4, p. 11]. Carbon dioxide can be supplied by fossil-fueled power plants, which can add value to their carbon dioxide byproduct by converting it to methane via hydrogen. Converting hydrogen and carbon dioxide into methane for direct injection into the natural gas grid is one of two main mechanisms of the Power-to-Gas methodology [17]. Power-to-Gas uses hydrogen and methane to store and distribute renewable energy.

IV. OPERATIONAL MODEL

In this section, we propose an operational model for hydrogen delivery using unmanned airships. Its goal is to efficiently deliver hydrogen within a known multiplier of optimum.

A. System Operations

The following list contains some operations that can be performed by multiple devices. For instance, hydrogen can be compressed by airships and by ground-based compressors. Knowing which device(s) can perform what operation(s) is important to determine assignments. Within constraints listed below in Section IV-B2, the heuristic assigns operations, for example,

Op1: Transport Hydrogen
- Load Hydrogen
- Unload Hydrogen

Op2: Transport Cargo
- Load Cargo
- Unload Cargo

Op3: Compress Hydrogen[1]

Op4: Hydrogenate CO_2 to Produce CH_4 and H_2O.

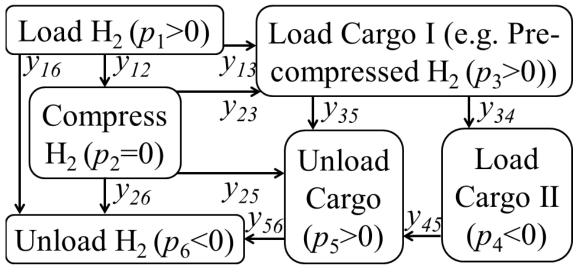
B. Optimizing Energy Harnessing

While hydrogen is being delivered, the airship can simultaneously be used to add value by an airship operator. How does an airship operator know whether to accept a shipping order? Generally, the operational cost is a function of the distance, weight, and time between nodes. The shipping rate is a function of the value added as perceived by the customer. If the shipping rate minus operational cost is a loss, then the airship operator would decide to not accept the shipping order.

1) Budget-Constrained Steiner Connected Subgraph Problem with Node Profits and Node Costs: Let us map this problem of deciding whether or not to accept a customer's shipping order to a problem referred to by Dilkina and Gomes [7] as the *Budget-Constrained Steiner Connected Subgraph Problem with Node Profits and Node Costs*. The costs are what the budget constrains. In our application, we budget the lifting capacity of the airship so that the airship always has enough lifting capacity to reach its next destination. Potential lift increases as hydrogen (uncompressed or compressed) is loaded. Compressed hydrogen may be later decompressed if the airship requires additional lift and has sufficient balloon capacity. Potential lift decreases as non-lifting-gas cargo is added. Separate from the budget-constrained costs is the unrelated variable, profit. Here *profit* has the common meaning as *yield*: revenue minus expenditures.

Fig. 2 shows an example of where up to two cargo loading stages and up to one unloading stage are considered. Fig. 2 shows a directed graph $G = (V, E)$ where each edge $ij \in E$ has a yield y_{ij} and each vertex $i \in V$ has a potential lift p_i. Let $T \in V$ be the terminals. E.g., the terminal set T would include the node labeled "Load Cargo I" if the airship operator were deciding whether to accept the corresponding customer's shipping order. Each weighted edge can be converted to a weighted node as Dilkina and Gomes [7] instruct by replacing each weighted edge with an artificial weighted node and by connecting that node to the endpoints of the replaced edge.

[1]As part of buoyancy management, some airships compress lifting gas [8].



y_{ij}: For each edge ij, y_{ij} is the yield the airship incurs by following ij.
p_i: For each vertex i, p_i is the change in potential lifting power.

Fig. 2: A weighted directed graph of some possible airship operations.

2) Objective Function: To formulate an objective function similar to that of Dilkina and Gomes [7], let H be a subset of the entire graph G shown in Fig. 2 such that H is the graph chosen by a heuristic which seeks to

$$\text{maximize} \sum_{ij \in E(H)} y_{ij} x_i x_j \tag{3}$$

where $E(H)$ is the edge set of graph H subject to

$$\sum_{i \in V(H)} p_i x_i \geq P \tag{4}$$

where P is the minimum lifting power required for the airship to reach its next destination where the binary variable

$$x_i \in \begin{cases} \{1\}, & \forall i \in T, \\ \{0, 1\}, & \forall i \in V. \end{cases} \tag{5}$$

The graph in Fig. 2 can be reformulated so that all weights are reflected on the edges. E.g., for each edge ij, let

$$p_{ij} = p_j - p_i. \tag{6}$$

If the lifting power of the airship is changed between nodes (e.g., hydrogen is consumed by the airship as fuel), then our expression for p_{ij} can reflect that loss by our adding the term $lift\_loss$. In that case, our expression for p_{ij} is

$$p_{ij} = p_j - p_i - lift\_loss. \tag{7}$$

3) Encoding: Now that we defined our objective function in Section IV-B2, the constraints of that objective function can be encoded. Dilkina and Gomes [7] offer three encodings, of which their adapted directed Dantzig-Fulkerson-Johnson (DFJ) formulation better approaches optimum.

V. CONCLUSION

Hydrogen's lifting power can theoretically augment its economic viability as an energy carrier. The logistics of that augmentation are mapped herein to an existing heuristic. That heuristic can be used to compute a set of operations/commands that when summed, add value.

The two major value-adding operations are these: 1) carry energy via hydrogen and 2) use the lifting power of hydrogen to transport goods. This is feasible in light of recent research on the safe use of of hydrogen as a lifting gas. Furthermore, the use of unmanned airships removes the risk to flight crews while reducing the cost of having flight crews.

A very large cargo-lifting airship can surpass the U.S. Department of Energy's FY2017 tube-trailer hydrogen carrying capacity goal by ten times (and a more conservatively-sized half-scale version of that airship can surpass the goal by five times). The airship simultaneously transporting goods, as well as performing other operations, suggests a viable pathway toward economically harnessing off-grid renewable energy.

For future work, we are planning to develop a simulator to evaluate our operational model and to quantify savings.

ACKNOWLEDGMENT

This work was partially supported by a National Science Foundation EAGER Award (IIS-1050301). We also thank the reviewers of an earlier version of this paper for their feedback.

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APPENDIX: DETAILS OF 11 000 KG OF HYDROGEN REACTING IN THE SABATIER PROCESS

Above, we showed that a hydrogen version of the conceptual CL 160 would have approximately 11 000 kg of excess hydrogen lifting gas. One possible use of that excess gas is to react it with ∼60 000 kg of carbon dioxide to produce ∼49 000 liters of water and ∼12 000 gigajoules of natural gas. Here we show how we calculated those amounts.

Recall that the Sabatier reaction is

$$4\,\mathrm{H_2} + \mathrm{CO_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O}. \qquad (2)$$

Since the input term of (2) specifying $\mathrm{H_2}$ is multiplied by a factor of 4, let us find the molar mass (M) of $4\,\mathrm{H_2}$. The molar mass of $4\,\mathrm{H_2}$ is calculated via hydrogen's relative atomic mass $\mathrm{A_r(H)}=1.008$ [13]. Thus,

$$\begin{aligned} \mathrm{A_r}(4\,\mathrm{H_2}) &= 4(2\,\mathrm{A_r}(\mathrm{H})) \\ &= 8(1.008) \\ &= 8.064 \implies \\ M(4\,\mathrm{H_2}) &= 8.064\ \mathrm{g{\cdot}mol^{-1}}. \end{aligned}$$

With $M(4\,\mathrm{H_2})$ known, we calculate the number of moles of $4\,\mathrm{H_2}$ in 11 000 kg of hydrogen to be

$$\begin{aligned} &(11\,000\ \text{kg of}\ 4\,\mathrm{H_2})M(4\,\mathrm{H_2}) \\ &= (1.1\times 10^{4}\ \text{kg of}\ 4\,\mathrm{H_2})/(8.064\ \mathrm{g{\cdot}mol^{-1}}) \\ &= (1.1\times 10^{7}\ \text{g of}\ 4\,\mathrm{H_2})/(8.064\ \mathrm{g{\cdot}mol^{-1}}) \\ &= 1.36\times 10^{6}\ \text{mol of}\ 4\,\mathrm{H_2}. \end{aligned}$$

By that quantity, we multiply (2) to produce

$$(1.36 \times 10^6 \text{ mol})(4\,\mathrm{H_2} + \mathrm{CO_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O}) \implies$$
$$(1.36 \times 10^6 \text{ mol})(4\,\mathrm{H_2}) + (1.36 \times 10^6 \text{ mol})(\mathrm{CO_2}) \longrightarrow$$
$$(1.36 \times 10^6 \text{ mol})(\mathrm{CH_4}) + (1.36 \times 10^6 \text{ mol})(2\,\mathrm{H_2O}). \quad (8)$$

We see in (8) that 1.36×10^6 mol of $4\,\mathrm{H_2}$ (11 000 kg) reacts with 1.36×10^6 mol of CO_2. To convert that molar quantity of CO_2 to units with which we are more familiar, we need the molar mass of CO_2, $M(CO_2)$. In same manner that we calculated $M(4\,\mathrm{H_2})$, we now derive $M(CO_2)$ via its relative atomic mass [13]:

$$\begin{aligned}\mathrm{A_r}(\mathrm{CO_2}) &= \mathrm{A_r}(\mathrm{C}) + \mathrm{A_r}(\mathrm{O_2}) \\ &= \mathrm{A_r}(\mathrm{C}) + 2\,\mathrm{A_r}(\mathrm{O}) \\ &= 12.011 + 2(15.999) = 44.009 \implies \\ M(\mathrm{CO_2}) &= 44.009 \text{ g·mol}^{-1}.\end{aligned}$$

With $M(CO_2)$, we find the equivalent of 1.36×10^6 mol of CO_2 to be

$$\begin{aligned}&(1.36 \times 10^6 \text{ mol of } \mathrm{CO_2})(M(\mathrm{CO_2})) \\ &= (1.36 \times 10^6 \text{ mol of } \mathrm{CO_2})(44.009 \text{ g·mol}^{-1}) \\ &= 5.99 \times 10^7 \text{ g of } \mathrm{CO_2} \\ &= 5.99 \times 10^4 \text{ kg of } \mathrm{CO_2} \\ &\approx 60\,000 \text{ kg of } \mathrm{CO_2}.\end{aligned}$$

Similarly, we calculate the molar mass $M(2\,\mathrm{H_2O})$ via the relative atomic mass of $2\,\mathrm{H_2O}$ [13], which is

$$\begin{aligned}\mathrm{A_r}(2\,\mathrm{H_2O}) &= 2(2\,\mathrm{A_r}(\mathrm{H}) + \mathrm{A_r}(\mathrm{O})) \\ &= 2(2(1.008) + 15.999) \\ &= 2(18.015) \\ &= 36.030 \implies \\ M(2\,\mathrm{H_2O}) &= 36.030 \text{ g·mol}^{-1}.\end{aligned}$$

Using that molar mass, we convert the molar quantity of $2\,\mathrm{H_2O}$ to liters:

$$\begin{aligned}&(1.36 \times 10^6 \text{ mol of } 2\,\mathrm{H_2O})(M(2\,\mathrm{H_2O})) \\ &= (1.36 \times 10^6 \text{ mol of } 2\,\mathrm{H_2O})(36.030 \text{ g·mol}^{-1}) \\ &= 4.90 \times 10^7 \text{ g of } 2\,\mathrm{H_2O} \\ &= 4.90 \times 10^4 \text{ kg of } 2\,\mathrm{H_2O} \\ &\approx 4.90 \times 10^4 \text{ L } (1.29 \times 10^4 \text{ gal}) \text{ of } 2\,\mathrm{H_2O}\end{aligned}$$

since one kilogram of water fills approximately one liter. (The 49 000 liters of water does *not* include the water made by natural gas customers who combine the Sabatier-reaction-produced CH_4 with atmospheric oxygen (O_2).)

We now convert the molar quantity of CH_4 to a trading unit of natural gas, gigajoules (GJ). Methane's heat of combustion is 890.71 ± 0.38 kJ·mol^{-1} [16]:

$$\begin{aligned}&(1.36 \times 10^6 \text{ mol of } \mathrm{CH_4})(890.71 \text{ kJ·mol}^{-1}) \\ &= 1.21 \times 10^9 \text{ kJ of } \mathrm{CH_4} \\ &= 1.21 \times 10^3 \text{ GJ of } \mathrm{CH_4}.\end{aligned}$$