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Electrolysis Ship for Green Hydrogen Production and Possible Applications

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Abstract**—**Green hydrogen is the most environmental, renewable alternative to produce hydrogen. However, an important challenge to make hydrogen a competitive energy carrier is a constant supply of renewable energy, such as solar, wind and hydropower. Given that the electricity generation potential of these sources vary seasonally and interannually, this paper proposes installing an electrolysis hydrogen production plant in a ship and move the ship to the locations where electricity is cheap, or where the seasonal potential for renewable generation is high. An example of electrolysis ship application is to produce green hydrogen with hydropower from the North region of Brazil and then sail to the Northeast region of Brazil and generate hydrogen using excess electricity from offshore wind power. The electrolysis ship concept is interesting because it has the flexibility to produce green hydrogen using the cheapest renewable electricity available in the market.

Keywords**—**Green hydrogen, electrolysis ship, renewable energies, seasonal variations.

I. INTRODUCTION

TWO of the main challenges to increase the viability of green hydrogen production is to have cheap and abundant sources of renewable energies, and electrolysis hydrogen production plants that operate with a high-capacity factor, 60 to 70% [1]. To achieve these high rates of hydrogen production, these plants should have the main purpose to produce hydrogen. If an electrolysis plant is used for energy storage, then the capacity factor reduces to 15 to 30%, which substantially reduces the viability of the plant [2].

The potential for wind and solar world potential for green hydrogen production has been mapped [3] and shows that it is challenging to find locations that have cheap, abundant, and constant renewable sources throughout the whole year. Even though there are several locations around the world where the solar power generation is relatively constant throughout the year, solar power can only provide a constant supply of electricity if an energy storage solution is built together with the solar plants, which substantially increases the price of the system [4].

Another option that has not yet been explored and increases the chances that the electrolysis plant will always have cheap, abundant, and a constant supply of renewable energy is to install the green hydrogen electrolysis plant in a ship. This substantially increases the flexibility of the plant. For example, the plant can use cheap wind power to produce hydrogen during the windy season in one location. When the windy season ends, the electrolysis ship can sail to another location with cheap and abundant hydropower renewable generation. Another option is to sail to a country connected to a large and robust grid in which the electricity prices are low due to a year with higher-than-average renewable generation.

The only proposal in the literature, which is similar to the one in this paper, is unmanned ships navigating the oceans, harvesting wind energy with cylindrical wind turbines and storing the electricity generation producing hydrogen. The ship would then return to the harbor with tanks full of hydrogen [5].

This paper is divided into four sections. Section II presents the electrolysis ship concept. Section III presents a case study for the implementation of electrolysis ships. Section IV concludes the paper.

II. HYDROGEN ELECTROLYSIS SHIP

An electrolysis ship plant consists of the components in Fig. 1: 1) seawater desalination plant, 2) hydrogen production electrolysis plant, 3) electricity generation plant, 4) hydrogen liquefaction plant, 5) deep seawater air-conditioning, 6) renewable generation alternatives, 7) deep ocean anchors or port, 8) substation and transmission, 9) transshipment LH2 delivery, 10) pipeline to the coast, 11) biomass oxycombustion power plant with CCS.

The seawater desalination plant on the ship is essential to allow it to produce the water required in the hydrogen production process. This allows the ship to produce hydrogen in any location where the ship can navigate, and where environmental restrictions allow. If the ship is designed to produce hydrogen within a large freshwater river, it might not require a desalination plant. However, the addition of a desalination plant substantially increases the operational flexibility of the plant.

The electrolysis production plant in the ship would consist of four to eight modular electrolysis hydrogen production plants with the intent of increasing the operational flexibility of the plant to vary the production of hydrogen according to the availability of intermitted renewable energy sources. The system could also be used as a demand side management solution for better integration to supply the energy needs of the location. The cooling system in the ship would use a seawater once-through cooling, if the environmental regulation permits, or a seawater cooling tower.

Apart from producing hydrogen with cheap renewable electricity, the ship can instead have a reversible fuel cell that

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can not only produce hydrogen for locations where the price of electricity is low, but also be used to generate electricity in locations where electricity costs are high. This would also increase the operational flexibility of the system, which could increase its viability. For example, during periods with very low renewable generation, the ship could use some of the hydrogen stored to generate electricity to supply the regional demand. However, ships for electricity generation will not require desalination plants and other equipment used to produce hydrogen. Thus, the arrangement used for each location will depend on the location need for energy storage and electricity generation. Depending on the occasion, it might be a better alternative to have two separate ships. One for producing hydrogen (electrolysis ship) and another to generate electricity (fuel cell ship). If there is both demand for hydrogen production and energy storage, the ship can produce hydrogen and electricity (reversible fuel cell ship).

Fig. 1 Electrolysis ship components

A substation and transmission lines are required to connect the ship to the electricity grid of the region, so that the ship can be used for demand side management or energy storage for the local grid. This is particularly convenient if the grid relies on wind and solar generation, in which the ship can be used to reduce the intermittency of these electricity generation sources. A benefit of using an electrolysis ship is that the ship can sail from one location to another depending on the cost of electricity; this would reduce the need for the construction of transmission lines connecting both locations.

The hydrogen produced could be delivered to the coast via an underwater pipeline if the location has demand for hydrogen. Or the hydrogen could be liquefied and delivered to a LH2 cargo ship to sell the hydrogen in the future hydrogen LH2 market. To increase the efficiency for liquefying the hydrogen to a temperature of -253 ^{o}C, the ship could have a seawater air-conditioning plant that extracts water at 3 to 5 ^{o}C at depth of 700 to 1000 meters to lower the energy consumption required to liquify the H_2 in up to 10 to 15% depending on the ambient temperature at sea level [6], [7].

The ship can operate floating on the sea or connected to the port. If the ship is floating on the sea and the location has demand for hydrogen, a pipeline could be built to transport hydrogen without the need for liquefaction. If the ship operates connected to a port, a pipeline is not required. Additionally, the oxygen produced in the electrolysis processes could be used in combination of a biomass oxycombustion power plant. Apart from increasing the electricity generation efficiency of the plant, another advantage of oxycombustion power plants is the lack of nitrogen in the exhaust gasses, which makes it much easier to capture the CO_2 for posterior storage [8].

III. CASE STUDIES

There are several arrangements for operating an electrolysis ship. This paper discusses the possibilities below:

1) Change in H_2 production location according to the seasonal availability of renewable energy generation.
2) Change in H_2 production location according to the price of electricity of regional grids.
3) Change according to the demand for hydrogen globally. For example, if the demand H_2 is higher in Europe, H_2 can be produced in Brazil, however, if the demand increased in Japan, the Electrolysis ship could move to Australia.

Fig. 2 shows possible operational arrangements that can be performed with an electrolysis ship. Fig. 2 (a) proposes that H_2 is produced with the ship using offshore wind power and exporting to the USA and Europe via liquid H_2 tankers from May to October. In Fig. 2 (b) H_2 is produced with offshore wind in the USA and UK and transporting the H_2 with pipelines, without the need to liquify it, from November to April. Fig. 2 (c) suggests that the demand of hydrogen in Japan and China increases substantially and that the same ships will move to Asia now produce H_2 from Indian offshore wind power and transport to Japan and China via liquified H_2 tankers, from May to October, and from November to April, H_2 is produced using solar power from Australia and transported via liquid H_2 tankers (Fig. 2 (d)).

Fig. 3 presents a proposal for the electrolysis ship for Brazil. In this case, existing dams of Belo Monte and Tucuruí have their generation capacity limited to the transmission costs of electricity from the North region to the Southeast region, where most electricity demand is in the country. This arrangement would allow these hydropower plants to increase their generation capacity from 11 GW for Belo Monto to 15 GW and Tucurui from 8 GW to 12 GW. This additional electricity generation during three or four months during the wet period would be used to produce hydrogen close to the hydropower plants, without the need for further investments in transmission.

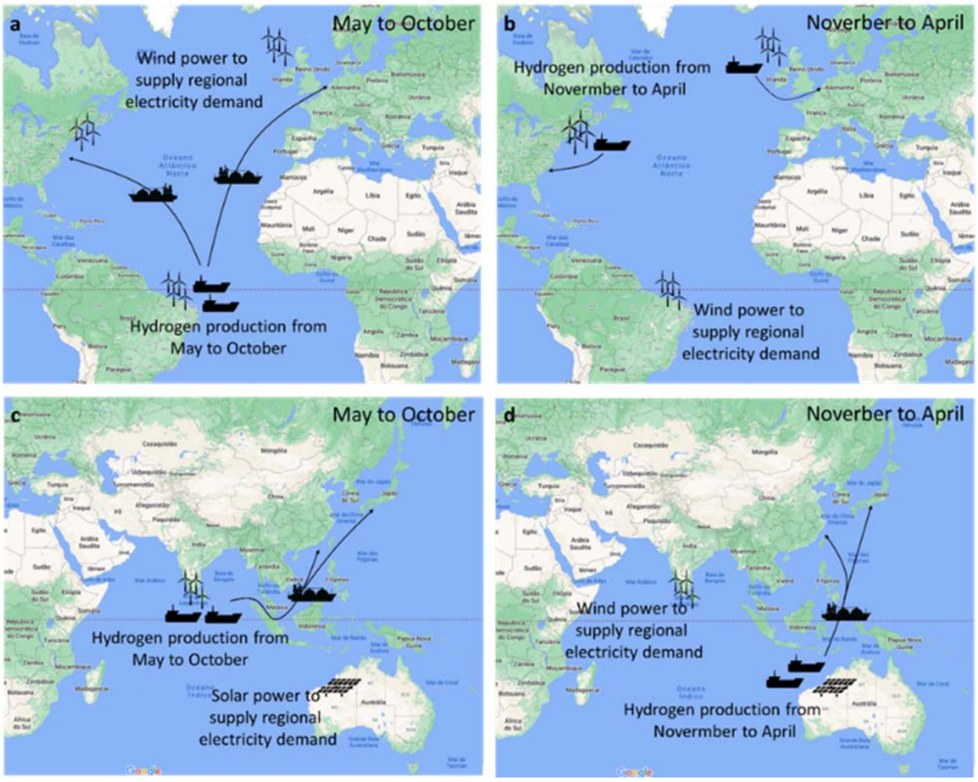

Fig. 2 Proposed case studies for the operation of electrolysis ships

Fig. 3 Proposed operation of electrolysis ships in Brazil

During the dry period, the electrolysis ship would then move to the Northeast region, where wind power capacities of onshore and offshore plants reach up to 80%. This is also convenient because the excess electricity generation in the region would not need to be transmitted to the Southeast region and would be used to produce hydrogen for exportation. This arrangement will be compared in future work to the alternative of having a fixed electrolysis plant between the hydropower plants in the North region of Brazil and the wind power plants in the Northeast region and the additional costs of transmission lines connecting both regions, which is equivalent to 1,500 km.

Fig. 4 Cheaper generation sources by country in early 2020 [10]

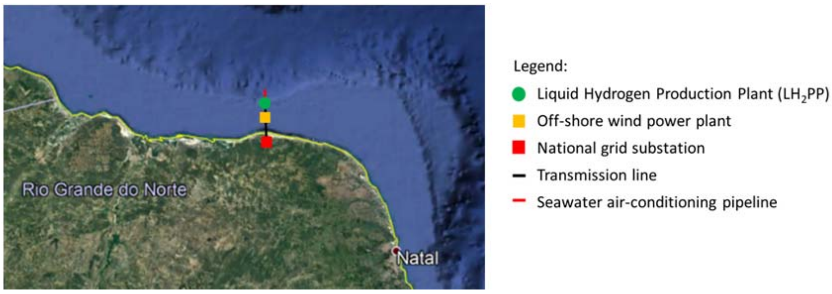

Fig. 5 Possible location for the liquid hydrogen production plant (PPLH)

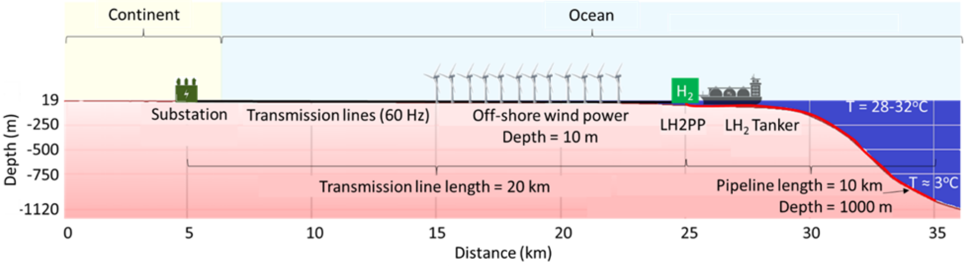

Fig. 6 Profile of the proposed project for H_2 production, liquefaction and export

TABLE I
DESCRIPTION OF THE ADVANTAGES OF USING OFF-SHORE WIND GENERATION FOR HYDROGEN PRODUCTION, DESCRIBED IN FIG. 6

Features	Advantages
Distancing from the SIN	The construction of off-shore wind power plants for hydrogen export is a good alternative for the initial production, liquefaction and export of hydrogen in Brazil because it is physically separated from the SIN plants and transmission lines, and thus become simpler to monitor the impact on the BIPS and develop the appropriate regulations for this type of procedure.
Desalination of sea water	With the above arrangement, the demand for water to produce H_2 would be met with the desalination of sea water, without the need to use water from the Northeast region, which is scarce. Due to the proximity to the continental shelf limit, the flow of concentrated salt can be directed to the seabed, minimizing the environmental impacts of desalination on the aquatic biome.
Depth for navigation	The continental shelf on the Northeast coast is very shallow, which makes it very difficult for ships with high drafts to export LH2 to the coast. With the PPLH close to the limit of the continental shelf, it facilitates the access of freighters to the PPLH.
Use of deep water for cooling [6]	With the proximity to the end of the continental shelf, it allows the PPLH to access water of 2-5 °C at a depth of more than 1,000 meters, with pipes of 10 km or less. The use of chilled water from the seabed has the ability to reduce electricity consumption for H_2 liquefaction by 10-15%, by reducing the maximum system temperature that liquefies from 28-32 °C (surface temperature of the Northeast coast) to 2-5 °C (water temperature at high depths).
Less impact on the aquatic environment	The proximity to the seabed can also reduce the environmental impacts on the aquatic biome around the PPLH, since part of the cold water with higher salinity can be directed to the seabed, without impacting the temperature and surface water salinity.
Increased fishing productivity	The increase in nutrients and, consequently, the pumping of deep waters has the potential to substantially increase fishing productivity on the Northeast coast. In addition, the cold water resulting from hydrogen liquefaction can be used to produce cold water fish such as Salmon, among others.
Features	Disadvantages
Offshore operation	The operation of the PPLH and the transfer of H2 to the freighter at the end of the continental shelf leaves the system susceptible to the action of large waves and storms, which can cause problems for the mooring of ships and the operation of the PPLH. In this case, a platform such as those for oil exploration and hydrogen cargo ships would need dynamic stabilization.
Very shallow waters	The continental shelf of the Northeast is very shallow, particularly in Rio Grande do Norte, with a depth of less than 10 meters, 20 km from the coast. This can hinder the access of the vessels needed to build the Off-Shore wind farm. There are already solutions with low draft vessels that rest on the seabed and make the foundations in piles to build the base of the tower. Then, that same vessel completes the construction of the turbine with the help of a crane.
Oxygen rejection	Another product of water electrolysis is oxygen. As the PPLH is located far from the coast, the use of the produced oxygen would have low viability and would have to be released into the atmosphere without any economic benefit. Oxygen can be used in industrial and hospital processes, to increase the efficiency of thermoelectric generation, among other services.

The emergence of the hydrogen economy is of great interest to Brazil because the country obtains the largest and most accessible onshore and offshore wind generation potential in the world [9]. Fig. 4 shows that the wind generation in Northeast Brazil is a cheaper source of electricity generation in the world. In addition, it holds vast potential for photovoltaic solar generation. This electric generation potential can be transformed into liquefied hydrogen and transported to Europe, Japan, the USA, China, or other countries that have a demand for hydrogen. As Brazil has already developed a sustainable solution for the transport sector with ethanol and biodiesel that has been competitive with oil for more than four decades, hydrogen production in Brazil should focus on the export of hydrogen. In addition, the biofuel developed in Brazil may be exported in the future for the operation of biorefineries in countries with low solar incidence, land and water availability.

An interesting location with good offshore wind generation potential [9], close to the European market and with a reduced continental plate that could be used for the production and liquefaction of H_2 for export is shown in Figs. 5 and 6. Table I presents the benefits of this arrangement.

IV. CONCLUSION

This paper has proposed the construction of electrolysis ships with the intention of increasing the operational flexibility of the plants and allowing the ship to move to locations with abundant renewables potential and cheap electricity for green hydrogen production. This alternative has particular potential in locations with highly seasonal renewable energy generation, as in the North and Northeast regions of Brazil.

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