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Chile and its Potential Role Among the Most Affordable Green Hydrogen Producers in the World

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As result of the adverse effects caused by climate change, the nations have decided to accelerate the transition of the energy matrix through the use of non-conventional sources free of polluting emissions. One of these alternatives is green hydrogen. In this context, Chile stands out for the exceptional climate that makes it a country with a lot of renewable resources. Such availability of resources gives the nation clear advantages for hydrogen production, strong gusts of wind throughout the country, the most increased solar radiation in the world, lower cost of production of electrical supplies, among others. Due to this, the nation would be between the lowest estimated cost for hydrogen production, i.e., 1.5 USD/kg H_2 approximately, scenario that would place it as one of the cheapest green hydrogen producer in the world.

Keywords: green hydrogen, renewable energy, global warming, CO_2, Chile

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INTRODUCTION

The irreversible impacts caused by climate change around the world have prompted different nations to sign agreements and pacts to decarbonize their energy sources (Osorio-Aravena et al., 2021; Yousef, 2021), especially in the energy sector (electricity, heating/cooling, and transport), what is the largest contributor to Global Greenhouse Gas (GHG) emissions (IPCC, 2014). Chile is no exception due to its constant exploitation of natural resources attributed mainly to its agricultural and mining activities (Reyes-Bozo et al., 2014). However, in addition to its commodities, the country has a unique climate and geography that position it as one of the territories with the highest solar and wind renewable resources in the world. For example, it has the Atacama Desert with increased solar radiation rates and Chilean Patagonia with the presence of strong gusts of wind (Simsek et al., 2019; Olivares et al., 2020). Therefore, such reasons have been sufficient to promote the replacement of fossil fuels with new alternatives to decarbonize their energy sources by using these resources. One alternative that has emerged in the last decade is the production of energy from the use of green hydrogen, that is, an element obtained from other substances that contain it through electrolysis and the use of renewable energies (Velazquez Abad and Dodds, 2020; Yousef, 2021).

Currently, renewable energies in the country represent approximately 43% of the installed capacity, with an estimated value of 9,651 MW. Meanwhile, a total of 69% of the renewable energy matrix comes from hydroelectric plants, followed by 14% from solar energy and 13% belonging to wind energy; the rest corresponds to other types of sources such as biogas and biomass (Becerra et al., 2017). In addition to this, in recent years, Chile has quintupled the capacity to generate electricity

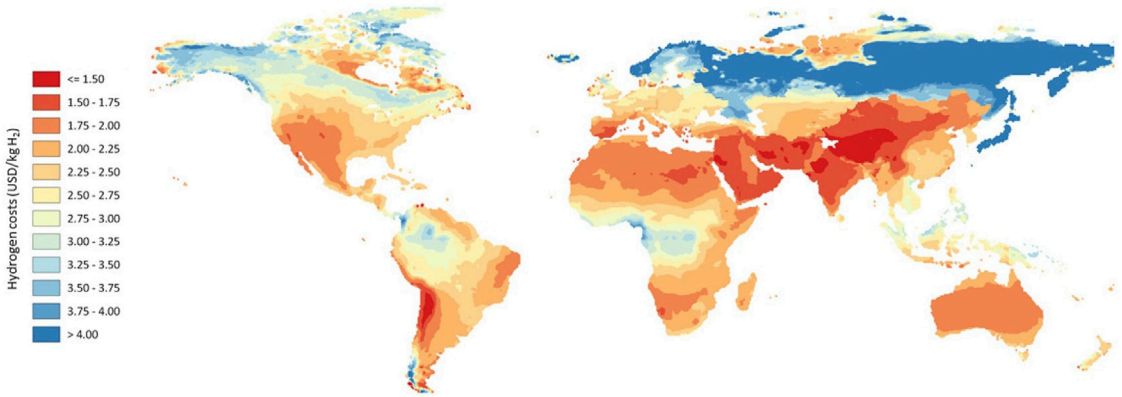

FIGURE 1 | Hydrogen production cost from hybrid solar PV and wind systems in 2030.

from these sources, and it is expected that by 2030, 60% of the electricity grid will come from renewable energies (Ministerio de Energía, 2017). Considering the above, Chile has baselines in terms of clean electricity production that make it a valuable potential to develop a hydrogen generation industry based on clean, renewable sources and become one of the leading exporters of bulk green hydrogen in the world (Ramirez Camargo et al., 2019; Fúnez Guerra et al., 2020).

The focus of this research is to contextualize in broad terms the situation of green hydrogen in Chile. It is presented some of its main production advantages in the national territory and the renewable resources that the country offers for it.

PRODUCTION ADVANTAGES

Chile has strategic zones throughout its vast geography with renewable potential for hydrogen production. For example, estimates have been made in search of quantifying the number of renewable resources that could be allocated for this purpose present in the country, where dimensions that the territory has quantities of over 1,800 GW of available renewable energy power, including 1,200 GW of photovoltaic solar power, 550 GW of concentrated solar power and 14.5 GW of wind power (Santana et al., 2014).

In "Geopolitical and Market Implications of Renewable Hydrogen" report of Harvard Kennedy School, (Pflugmann and de Blasio, 2020), indicate that Chile have the renewable and freshwater resources potential to satisfy their renewable hydrogen demand through domestic production. While these countries are potentially self-suficient, they may still complement domestic production with imports due to cost considerations. While that the (International Energy Agency, 2021) (IEA), considering that the low-cost electricity can boost electrolysed hydrogen production, as they account for 50–90% of the overall levelised cost of hydrogen production. And countries or regions like Australia, China, Chile and the Middle East have a comparative advantage in the levelized costs of hydrogen production from renewable energy sources, mainly due to the low costs of photovoltaic solar and wind energy (**Figure 1**). Additionally (BloombergNEF, 2021), also positions Chile with competitive costs in renewable green hydrogen by 2030, along with Brazil, India, Perú, U.S. and U.A.E.

From this perspective, the high availability of energy resources makes it easier to obtain electricity from renewable sources at a lower cost, where the approximate Levelized Cost of Electricity (LCOE) for solar PV generation, Wind generation and PV + Wind generation across the continental Chilean territory, assuming a weighted average cost of capital (WACC) of 7%, is expected to fall from a range of 20.2–42.6 €/MWh and 19.1–44.1 €/MWh to 7.5–16.1 €/MWh, and 7.3–16.7 €/MWh by 2050, respectively (Osorio-Aravena et al., 2021). Such a decrease in the cost of energy inputs positions Chile with a clear and strategic advantage in terms of energy inputs to obtain clean electricity, which can easily be distributed to feed electrolysis processes for hydrogen generation, which will allow a competitive large-scale production of the element for use in the national network, third parties and also as a future exporter (Tlili et al., 2019; Gallardo et al., 2021).

Considering the above, the green hydrogen produced in the Atacama desert (Northern Chile) and the Magallanes region (Southern Chile) would be of the cheapest to make in terms of levelized production costs on the planet by 2030. It is estimated that its value will continue to decrease by 2050, reaching values that reach 1.1 to 0.8 USD per kg of H_2 produced, where an annual production capacity of 160 thousand tons of H_2 would be estimated. Such figures make Chile economically attractive for investment, considering that by 2030 in EU and the United States the levelized costs of producing hydrogen would reach 2.6 and 2.1 USD/kg H_2 (Tlili et al., 2019; Hurtubia and Sauma, 2021), a reduction of at least 33% in the levelized costs of H_2 compared to the case of northern Chile, which would reach a value of 1.4 USD/kg H_2 for the same period, this without considering costs of transportation, distribution, among others. (Biggins et al., 2022), on the other hand, mentions that although the price is one of the lowest in the world, the costs of storage, compression, transportation, and others would not compensate for its low price, however, the German Corporation for International

Cooperation (Tractebel/Engie Impact, 2021) contradicts (Biggins et al., 2022), mentioning that global alliances and policies, as well as multinational agreements, would facilitate mutual collaboration between countries to reduce commercial limitations. In addition to economic advantages, (Baeza Virgilio, 2019) and (Ministerio de Energía, 2022) mention that the country also has other advantages regarding to production, transportation, and consumption, that classify as an important actor in the production of green hydrogen. Some advantages are:

- The highest global horizontal radiation potential (GHI) globally with values above 7 kWh/m^2 per day and 2,800 kWh/m^2 per year.
- Existence of desalination plants (mining activity) and desert areas with less environmental impact on communities.
- Existence of port infrastructures, railway lines, water, and gas transport in the same area due to its strong economic activities.
- Imminent need to integrate solar and wind energy for sustainable mining and reduce fossil fuel consumption.

GREEN HYDROGEN IN THE NATIONAL ENERGY MATRIX

Along with the potential to become a major player in H_2 exports in the world, the production of green H_2 in Chile would help to meet the rising internal energy demand for one of its main economic activities, as mineral exploitation industry, considering the projections (made by Chilean Copper Commission, COCHILCO) on accumulated demand of electrical power required by copper mining between the years 2021 and 2031 (Brantes et al., 2020). (Armijo and Philibert, 2020), on the other hand, indicate that renewable resources could ultimately supply the accumulated energy demand required by the copper mining industry. For the years 2025 and 2030, according to COCHILCO, a demand of 974 and 1,194 MW is estimated, which would correspond to 6.71% and 8.23% of the total available wind energy (14.5 GW), while that the energy demand would only reach 0.081% and 0.099% of the total estimated photovoltaic resources (1,200 GW).

The incorporation of green H_2 as energy resource to the national energy matrix will be the introduction to the development of an clean energy industry, with the least amount of emissions, and it is estimated that will create an economic sector comparable to the mining industry (Fúnez Guerra et al., 2020). The growth of the industry will unfold in different stages, generating new products in different periods. In the short term (to the year 2025), both imported hydrogen in oil refineries and national production and conventional fuel in public transport as well as in high-tonnage machinery and CAEX trucks as a result of intense competition in hydrogen generation will be replaced (Fúnez Guerra et al., 2020; Hurtubia and Sauma, 2021). Public action will launch the local hydrogen industry by promoting green products and increasing its demand. New market demands will boost the technical knowledge, innovation and investigation, deployment in terms of infrastructure, and financing by companies (El-Emam and Özcan, 2019; Ghaebi Panah et al., 2022), thus generating an industry prepared to compete internationally.

The introduction of H_2 to the internal energy network will contribute to the reduction of GHG caused by mining activity (Reyes-Bozo et al., 2014), for example, the partial replacement of Diesel fuel by Hydrogen in CAEX-type high-tonnage trucks with dual engines that use a mixture of hydrogen and diesel as fuel would help reduce estimated amounts of 450 kton and 2,500 kton of CO_2 by 2030 and 2050 (Guerrero Gómez, 2020; Brantes and Cantallopts, 2021) in loading and extraction activities in open-pit mining. On the other hand, in long-term between 2025 and 2030 onwards, massive production of ammonia, hydrogen, and biofuels for the decarbonization of the air and maritime transport sector would already increase (Tlili et al., 2019; Xin, 2021), increasing the exports as the demand for clean fuels increases.

Although the scenario of green H_2 in Chile is promising for the development of a sustainable future, there are many barriers to positioning the country as one of the leading international exporter of hydrogen affordable, one of them, as mentioned by (Gallardo et al., 2021) is the consolidation of policies, technical knowledge and national infrastructure present in the territory to promote local professional talent in hydrogen, which would give way to Chile to entry in international markets. In agreement with the above (Haas et al., 2018), mention that there are still current barriers to the massive deployment of solar technologies in Chile, like the early development of the solar market, a low number of investment companies, high costs of sale of PV systems and variable prices of energy in Chile, barrier also mentioned by (Ramirez Camargo et al., 2019), referring to the extensive geography of the country and its multiple electrical networks, which represents a obstacle to the extension of projects with use of renewable energy that could be linked to the hydrogen market.

The production of green H_2 in Chile has been strongly promoted by the Production Promotion Corporation (CORFO, by its acronym in Spanish), creating international consortiums to carry out projects for its production and use in several sectors, like mobility, production of green ammonia (NH_3), supply to public and railway transport or bio-fuels for automobiles such as kerosene.

CURRENT AND FUTURE GREEN H_2 PROJECTS

One of the projects close to starting operations in Chile corresponds to the Haru Oni project, also called the HIF Project, of the company with the same name, which together with the Siemens Energy group, Porsche, Enel, and other collaborators lead the development of the first plant producer of synthetic methanol, which will be used to obtain synthetic gasoline (Enel Chile, 2020; Peña, 2021). This project will be located in a region characterized by having strong gusts of wind, which will provide movement to wind turbines for the generation of electricity, which, together with obtaining water

FIGURE 2 | The world's 20 largest announced giga-scale green hydrogen projects. HyDeal Ambition (67 GW)—Western Europe (1); Unnamed (30 GW)—Kazakhstan (2); Western Green Energy Hub (28 GW)—Australia (3); AMAN (16 GW)a–Mauritania (4); Asian Renewable Energy Hub (14 GW)—Australia (5); Oman Green Energy Hub (14 GW)a–Oman (6); AquaVentus (10 GW)—Germany (7); NortH2 (10 GW)—Netherlands (8); H2 Magallanes (8 GW)—Chile (9); Beijing Jingneng (5 GW)—China (10); Project Nour (5 GW)a–Mauritania (11); HyEnergy Zero Carbon Hydrogen (4 GW)a–Australia (12); Pacific solar Hydrogen (3.6 GW)—Australia (13); Green Marlin (3.2 GW)—Ireland (14); H2-Hub Gladstone (3 GW)—Australia (15); Moolawatana Renewable Hydrogen Project (3 GW)a–Australia (16); Murchison Renewable Hydrogen Project (3 GW)—Australia (17); Unnamed (3 GW)—Namibia (18); Base One (2 GW)a–Brazil (19); Helios green Fuels Project (2 GW)—Saudi Arabia (20) (IRENA, 2022).

from a desalination plant, will be the raw materials for the separation and obtaining of H_2 through the electrolysis process (Siemens Energy, 2020). The hydrogen obtained will be mixed with carbon monoxide captured from the atmosphere through filters and synthesized to obtain methanol, the primary raw material for the production of biofuels. Such project was estimated to produce an amount of around 70,000 m^3 per year of synthetic gasoline (Siemens Energy, 2020). It is considered that the project will start in 2022 in its pilot phase and begin its industrial operations by 2024, being the first plant of its kind to produce hydrogen and green fuels in Latin America. On the other hand, Anglo American mining company has been a pioneer in using green hydrogen in the national territory. By 2021, the company managed to produce the first green hydrogen molecule to supply fuel to vehicles with zero carbon emissions in its operations. The hydrogen generated from the process is obtained through a generator module, fed by recirculated water from its concentrator processes, and others, which acts through electrolysis where it separates hydrogen as its main product and the oxygen that is returned to the environment (Anglo American, 2019). Currently, the module supplies clean energy to a forklift in operation and has a generation capacity of 2 kg/H_2 per day. In addition, the module is powered by electricity generated by two photovoltaic plants (Anglo American, 2019).

The portfolio of future projects that contemplate the use and development of hydrogen as an energy alternative in Chile is extensive. The Chilean Energy Ministry indicate that there are more than 40 projects in different phases, from the presentation of the resolution of environmental impact until the start-up of its pilot scale (Ministerio de Energía, 2017; Peña, 2021). Considering the number of projects related to the field of green hydrogen, Chile makes optimistic calculations about its future in this industry, among some of which stand out: green hydrogen production globally with costs less than 1.5 USD/kg H_2; 5 GW of operational power in terms of water electrolysis technologies; Annual production of at least 200 kton of hydrogen-based on renewable energies; Leaders in Latin America in production through electrolysis and the export of green hydrogen and its derivatives by 2030 (Ministerio de Energía, 2017).

Finally, the future perspectives of announced H_2 projects around the world, mainly in Australia, China, Japan or the EU (International Energy Agency, 2019), prove again the efforts that is making Chile to lead the production of green hydrogen in Latin America (**Figure 2**), while its solar and wind potential provide competitive advantages to renewable energy in meeting domestic energy demand, and depending on the distribution cost structure, it could become a world-class renewable energy exporter.

CONCLUSION

In perhaps the most contested decision in Glasgow (in the context of the 26th United Nations Climate Change Conference in 2021, COP26), countries ultimately agreed to a provision calling for a phase-down of coal power and a phase-out of "inefficient" fossil fuel subsidies (UN, 2021). Then, to strike this objective, some countries around the world are looking towards green hydrogen as a potential technology to reduce their reliance on fossil fuels, increasing the exploitation of renewable resources and meeting their global climate commitments.

Chile has high renewable resources available, such as the most increased solar radiation in the world (9 kWh/m2 per day in summer), or strong gusts of wind (8 m/s) in the northern and southern of the country, along with solid economic activities and installed infrastructure that promote competitive advantages over other countries for the production and export of green hydrogen regionally or globally. The above lays the foundations to consolidate the Latin American country as one of the cheapest green hydrogen producer in the world, with an average value of 1.5 USD per kg of hydrogen produced, compared to other world powers such as China and the United States with market values that reach 2.2 and 2.6 USD/kg H_2 for the year 2030. It is forecast that such price decreases over the years until reaching prices close to 1.0 USD/kg of H_2 for 2050.

However, such a purpose is still far from being achieved since factors such as the lack of investment in technology, human capital, government energy policies, as well as the immature development of the solar market in the country constitute the main barriers that have hindered the approbation, implementation, and installation of projects that involve the use of electrolysis technologies for the production of green fuel in the national territory. Finally, the preceding has not impeded carrying out large-scale projects related to green hydrogen.

AUTHOR CONTRIBUTIONS

KA, MS, and NT contributed in research and wrote the paper. IS, JR, and AN contributed with research, review and editing. All authors have read and agreed to the published version of the manuscript.

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