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*Perspective*

# Exploring the Potential of Green Hydrogen Production and Application in the Antofagasta Region of Chile

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**Abstract:** Green hydrogen is gaining increasing attention as a key component of the global energy transition towards a more sustainable industry. Chile, with its vast renewable energy potential, is well positioned to become a major producer and exporter of green hydrogen. In this context, this paper explores the prospects for green hydrogen production and use in Chile. The perspectives presented in this study are primarily based on a compilation of government reports and data from the scientific literature, which primarily offer a theoretical perspective on the efficiency and cost of hydrogen production. To address the need for experimental data, an ongoing experimental project was initiated in March 2023. This project aims to assess the efficiency of hydrogen production and consumption in the Atacama Desert through the deployment of a mobile on-site laboratory for hydrogen generation. The facility is mainly composed by solar panels, electrolyzers, fuel cells, and a battery bank, and it moves through the Atacama Desert in Chile at different altitudes, from the sea level, to measure the efficiency of hydrogen generation through the energy approach. The challenges and opportunities in Chile for developing a robust green hydrogen economy are also analyzed. According to the results, Chile has remarkable renewable energy resources, particularly in solar and wind power, that could be harnessed to produce green hydrogen. Chile has also established a supportive policy framework that promotes the development of renewable energy and the adoption of green hydrogen technologies. However, there are challenges that need to be addressed, such as the high capital costs of green hydrogen production and the need for supportive infrastructure. Despite these challenges, we argue that Chile has the potential to become a leading producer and exporter of green hydrogen or derivatives such as ammonia or methanol. The country's strategic location, political stability, and strong commitment to renewable energy provide a favorable environment for the development of a green hydrogen industry. The growing demand for clean energy and the increasing interest in decarbonization present significant opportunities for Chile to capitalize on its renewable energy resources and become a major player in the global green hydrogen market.

**Keywords:** green hydrogen; Chile; Antofagasta desert; Electrolyzer; green ammonia; carbon neutrality

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## 1. Introduction

Green hydrogen (GH) is a clean energy carrier that can be produced by splitting water molecules into hydrogen and oxygen using renewable energy sources, such as solar, wind, or hydro power. The hydrogen produced in this way has no carbon footprint and can be used in several industries, including transport [1], manufacturing [2,3], and power generation [4–6]. In addition to its direct application as a fuel source, GH plays a vital role as a versatile raw material to produce various synthetic hydrocarbon fuels. These synthetic fuels, commonly referred to as "electro fuels" or "E-fuels," are derived from the utilization of captured carbon dioxide or the separation of nitrogen from the atmosphere through a reaction with GH. Some examples of e-fuels include E-methanol, E-methane, and E-ammonium [7–9]. Chile is a country with a tremendous potential for renewable energy, particularly in solar, tidal, and wind power [10,11]. As such, the country has established a goal of attaining carbon neutrality by 2050 [12]. The production of green hydrogen is seen as a key element to accomplish this target [12,13]. Figure 1 shows a visual representation of the main energy projects currently in progress [14]. Comprehensive information about these initiatives is available in Table S1 in the supporting information. In addition, the country is also aiming to reduce its reliance on fossil fuels, especially in the mining and transportation sectors.

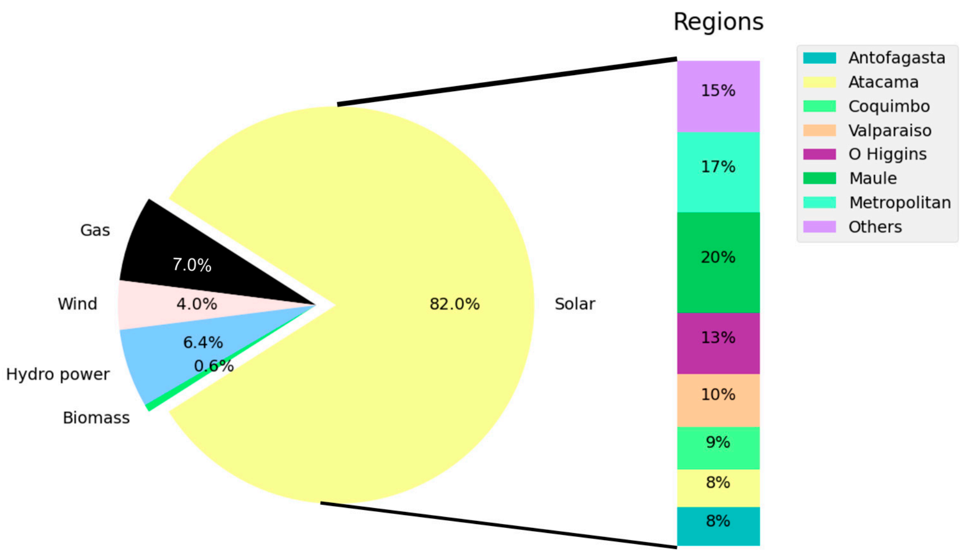


**Figure 1.** A list of projects currently declared under construction in 2021. The colorbar illustrates the distribution of solar plants across various regions in Chile, representing the respective percentages.

In addition to its abundant renewable energy sources, Chile is well positioned to development a green hydrogen industry, including its advantages for accessing export markets, including those in Asia and Europe [15,16], and its strategic location as a hub for energy trade between the Americas and the Pacific [10]. In 2020, the Chilean Government released the national GH strategy, which is a long-term plan to establish a competitive hydrogen industry based on renewable resources, with the goal of becoming the world's most cost-effective GH producer by 2030, together with positioning Chile as one of the leading exporters of hydrogen by 2040 [13]. The strategy entails a three-stage plan to accelerate the deployment of GH-based technologies in multiple economic sectors and critical applications within the country [17]. The first stage of the strategy focuses on tapping the domestic market and proposes the implementation of GH in six primary applications: (i) refineries, (ii) ammonia, (iii) mining haul trucks, (iv) long-range buses, (v) heavy-duty trucks, and (vi) blending GH into the gas network [12,13]. The second stage involves the expansion of green ammonia production on a larger scale, promoting the entry of the country into international markets through the establishment of commercial agreements. This strategic approach aims to enhance the economic viability of the green hydrogen market. In the third and final stage, Chile seeks to become a leading global supplier of clean energy by expanding and diversifying green ammonia exports into new applications, such as maritime transport, as well as synthetic fuels for the aviation industry [18].

Notably, three of the six applications of the first stage are directly associated with mining activities, namely, mining haul trucks, long-range buses, and heavy-duty trucks.

The mining industry is a significant contributor to the country's economy and plays a crucial role in promoting the use of GH. Copper, being a well-known commodity, is a key driver of this growth.

Figure 2 shows the approximate location of GH projects across various regions of the country, organized by their corresponding application sectors. Further details of these projects are listed in Table 1. It is worth noting that a significant portion of these projects are concentrated in the Antofagasta region, which is located at the central part of the Atacama Desert. This location has been chosen strategically due to two primary reasons: firstly, the significant availability of renewable resources in the area (especially sunlight), and, secondly, the well-established and thriving mining industry in the region. As a result, the Antofagasta region offers a highly favorable location for the successful implementation of GH projects [19].

**Table 1.** List of $H_2$ projects along of Chile showed in Figure 2.

| **Hydrogen Projects in Antofagasta Region** | |
|---|---|
| 1 Amer H2 (Methanol)<br>2 Cerro Pabellón ($H_2$: LD *)<br>3 Planta Movil H2V ($H_2$: LD)<br>4 Pauna Greener Future ($H_2$, $HN_3$: LD, Ex †)<br>5 San Pedro de Atacama ($H_2$: LD)<br>6 Power to ammonia AES Andes ($NH_3$: Ex)<br>7 HOASIS ($NH_3$: LD, Ex)<br>8 Faraday ($NH_3$: Ex)<br>9 H2 solar projects ($H_2$: LD)<br>10 Cerro Dominador ($H_2$: LD) | 11 Hydra ($H_2$: LD)<br>12 Tren a hidrogeno ($H_2$: LD)<br>13 HyEx ($NH_3$: LD Ex)<br>14 Tango ($NH_3$: Ex)<br>15 Proyecto H2V GNA ($H_2$: LD)<br>16 Proyecto H2V Inversiones Farias ($H_2$)<br>17 Genesis ($H_2$: LD)<br>18 Paracelsus ($H_2$: LD)<br>19 METH2 Atacama (E-Methanol: LD, Ex) |
| Hydrogen projects in other Regions | |
| (B) Coquimbo Region (LD):<br>- H2GN ($H_2$) | (F) Aysen Region (LD)<br>- Mowl ($H_2$)<br>- Renewsatable Koste Alke ($H_2$) |
| (C) Valparaiso Region (LD):<br>- San Antonio Port ($H_2$)<br>- HyPro Aconcagua ($H_2$)<br>- Bahía Quinteros ($H_2$) | (G) Magellan Region (Ex)<br>- Llaquedona ($NH_3$)<br>- Pionero ($NH_3$)<br>- H2 Magallanes ($H_2$ and $NH_3$)<br>- Proyecto HIF and Haru Oni (E-Methanol and e-gas)<br>- Vientos Magallanicos ($NH_3$)<br>- H1 Magallanes ($NH_3$)<br>- HNH ($NH_3$)<br>- Cabeza de Mar ($NH_3$)<br>Gente Grande ($NH_3$) |
| (D) Metropolitan Region (LD):<br>- Gruas Horquillas FC ($H_2$)<br>- Estación hidrogeno Aeropuerto ($H_2$)<br>- Hydrogen Generator Unit ($H_2$)<br>- Proyecto Minera San Pedro ($H_2$) | |
| (E) Biobio Region (LD)<br>- Green Steel project ($H_2$)<br>- Zorzal ($H_2$)<br>- HVallesur ($H_2$)<br>- Kallsaya ($H_2$)<br>Proyecto USCS ($H_2$) | |

* LD: Local demand, † Ex: Export.

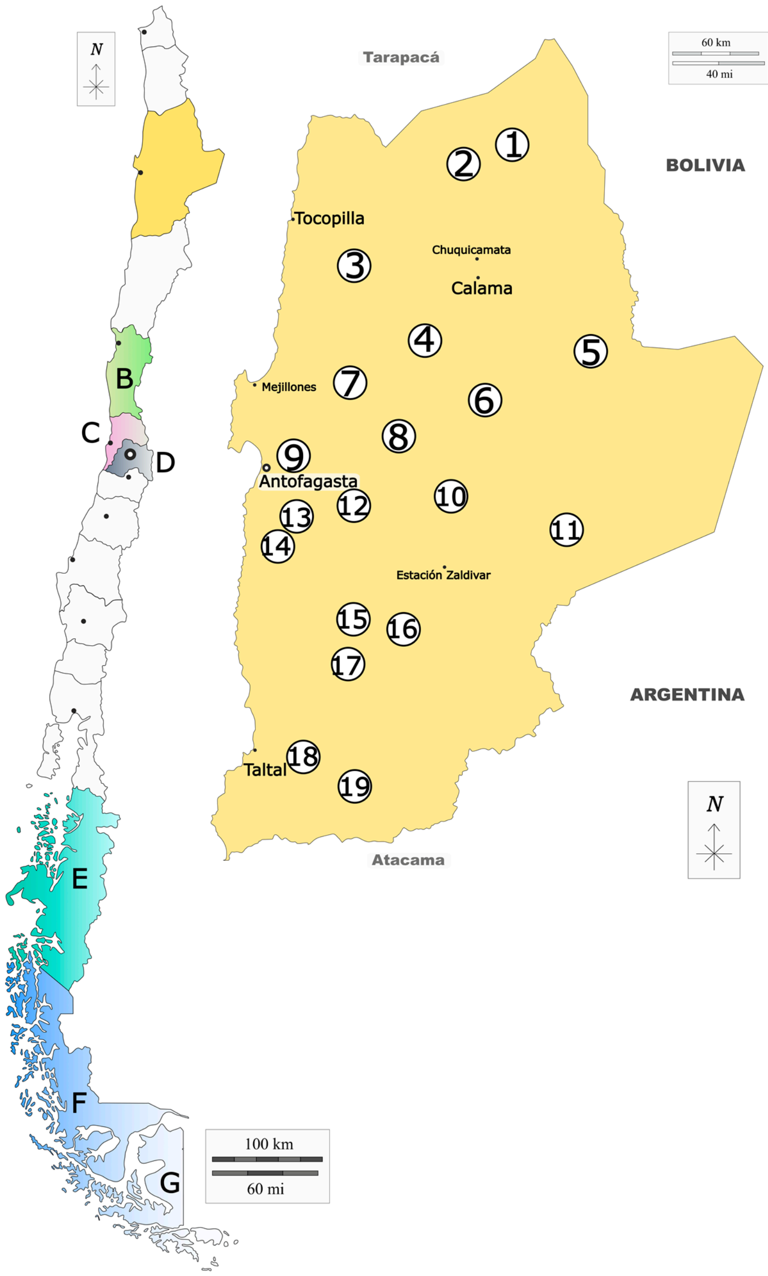


**Figure 2.** Map of undergoing $H_2$ projects along of Chile and zoom around Antofagasta region. The black dots represent the capital city of each region.

This work provides a comprehensive and brief overview of the potential for hydrogen generation in the diverse locations of the Antofagasta region by synthesizing relevant data from several reports. Moreover, the study introduces a novel Green Hydrogen Mobile Pilot Plant dedicated to mapping the real GH generation potential across the Atacama Desert. The mobile facility traversed the region, using sunlight to produce hydrogen, and simultaneously measuring efficiency and other crucial factors under realistic field conditions. The results of this approach reinforce the potential of the Antofagasta region for hydrogen generation. Furthermore, the paper reports on a forthcoming measuring campaign, which aims to offer policymakers and industry stakeholders valuable field data. This data will be vital for promoting the development of the hydrogen industry in the region, and, consequently, aid in meeting global climate targets.

## 2. Antofagasta as a HUB of Green Hydrogen

The National Energy Commission of Chile (Comisión nacional de Energía de Chile, CNE) has recently released the preliminary demand report for the period of 2021–2041 in the country, which projects a progressive rise of energy demand for the production of GH during that period. The report indicates that the energy demand is expected to increase from 199 GWh in 2023 to 40,636 GWh in 2041 in order to achieve global carbon neutrality [20]. To meet this demand, a gradual integration of operational projects is necessary. In this scenario, the Atacama Desert becomes a key location for the development of large-scale PV and CSP systems, owing to its status as one of the regions with the highest levels of solar radiation worldwide (see Figure 3).

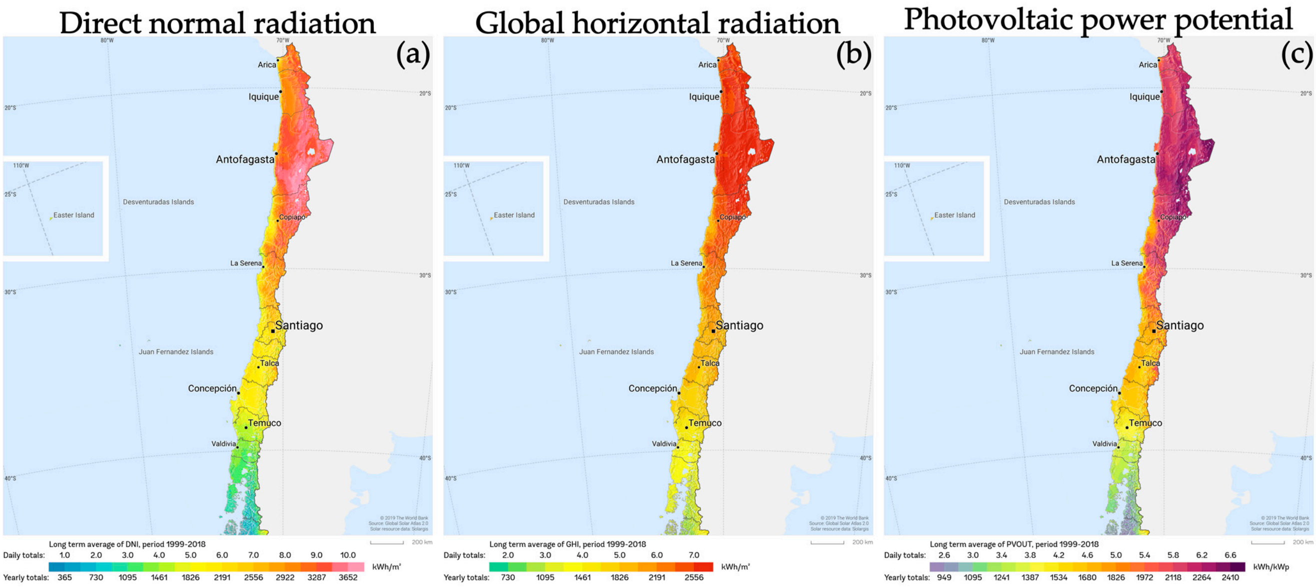


**Figure 3.** Long term average solar potential of part of Chile between 1999–2018: (**a**) direct normal radiation, (**b**) Global horizontal radiation and (**c**) photovoltaic power [21].

The project map released by the Chilean association of renewable energies and storage (ACERA, Asociación Chilena de Energías Renovables y Almacenamiento) reveals that the Antofagasta region will witness a significant influx of 123 photovoltaic solar projects in the near future. A detailed breakdown of the number of projects and their corresponding power output for each stage is provided in Table 2. Furthermore, the geographical locations (approximately) of the solar photovoltaic projects are displayed in Figure 4.

**Table 2.** List of energy projects under development in Antofagasta and total power (MW).

| Technology | Status of the Project | | | | | | | | | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Approved | | Under Construction | | Under Classification | | Testing | | Operational | | | |
| | # † | MW | # | MW | # | MW | # | MW | # | MW | # | MW |
| Solar photovoltaic | 56 | 8120 | 21 | 1366 | 7 | 2802 | 9 | 755 | 30 | 1669 | 123 | 15,012 |
| Solar photovoltaic + BESS * | 2 | 235 | 3 | 259 | 1 | 85 | 0 | 0 | 0 | 0 | 6 | 579 |
| Thermosolar | 7 | 1687 | 0 | 0 | 1 | 300 | 0 | 0 | 1 | 108 | 9 | 2045 |
| Geothermal | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 33 | 1 | 39 | 2 | 72 |
| Eolic | 10 | 2645 | 3 | 280 | 4 | 2055 | 1 | 12 | 6 | 793 | 24 | 5785 |
| BESS | 2 | 168 | 1 | 2 | 1 | 57 | 0 | 0 | 3 | 52 | 7 | 279 |
| Carnot battery | 0 | 0 | 0 | 0 | 1 | 560 | 0 | 0 | 0 | 0 | 1 | 560 |
| Biomass | 1 | 322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 322 |

* BESS: Battery Energy Storage Systems; † #: number of projects.

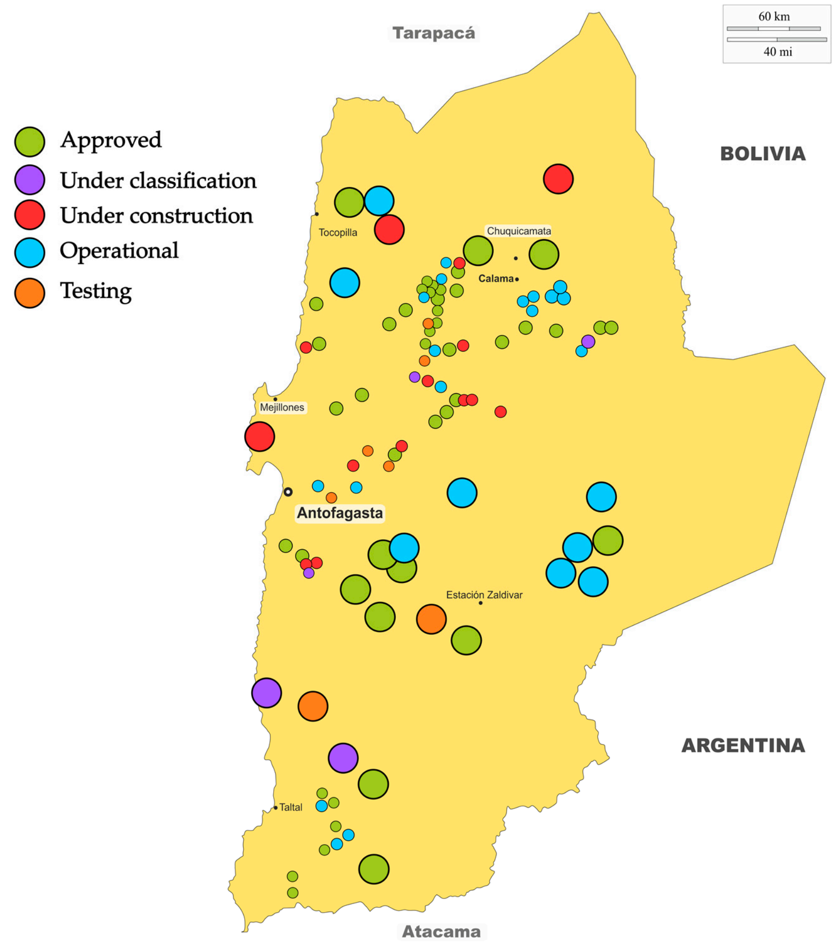


**Figure 4.** Photovoltaic solar energy projects in the Antofagasta region.

Having an understanding of the solar spectrum is critical in designing and studying numerous technologies [22]. It is important to investigate the performance of photovoltaic modules after their manufacture. According to the literature, it is mentioned that there are two methods to evaluate the performance of PV modules: power analysis and energy analysis [23]. Generally, the power is measured under standard test conditions (STC), that is, spectral distribution with AM 1.5 air mass at a temperature of 25 °C and an intensity of 1000 $Wm^{-2}$. This approach makes necessary to assume that the modules are installed in places where STC conditions are unlikely to occur. Therefore, evaluating the performance of PV modules by power may not be a suitable option if the STC conditions are not met. On the other hand, the energy rating of the module plays a fundamental role to measure the performance in field conditions [24]. In the latter, the energy rating of the module is determined by measuring its characteristics along with the corresponding data on environmental conditions. In this regard, the in situ measurement of PV modules is imperative to accurately evaluate their operational performance under realistic environments. The adoption of such a measurement process has become a prerequisite for ensuring the reliable assessment of PV modules.

*Green Hydrogen Mobile Pilot Plant*

Numerous research centers are dedicated to exploring the potential applications of green hydrogen in Chile. Among these institutions, the "Centro de Investigación Científica y Tecnológica de la Minería" (CICITEM) focuses on developing innovative solutions and technologies for the mining industry. CICITEM has recently undertaken a project named the "Green Hydrogen Mobile Pilot Plant (Planta Piloto Portable de Hidrógeno Verde, P3H2V)". The aim of this project is to assess and delineate the efficiencies of the production and use of hydrogen within the context of the Atacama Desert, particularly in proximity to mining operations located in the region. These mining activities represent a significant potential market for hydrogen as an energy carrier or renewable fuel. This mobile pilot plant employs an electrolysis process to divide water into hydrogen and oxygen, storing the hydrogen in high-pressure tanks for later use. The P3H2V plant is designed to evaluate the feasibility and effectiveness of green hydrogen production under different environmental conditions and scenarios. It boasts a production capacity of up to 0.5 $Nm^3$ of hydrogen per hour. The main objective of this initiative is to demonstrate the viability of producing green hydrogen using renewable energy sources in a variety of settings, with a specific focus on its potential application in the mining sector. This pilot plant is part of a broader effort by CICITEM to promote the use of green hydrogen as a sustainable and clean alternative to fossil fuels. The lack of empirical investigations related to hydrogen production in the Antofagasta region has generated considerable uncertainty regarding the development of this nascent industry. To address this knowledge gap, the P3H2V plant will facilitate a comprehensive investigation into the feasibility and sustainability of hydrogen production in this region.

Figure 5 displays a schematic representation (Figure 5a) and a corresponding photograph (Figure 5b) of the P3H2V during its initial measurements conducted within the Atacama Desert. The sequence of elements showed in a, arranged from left to right, comprises photovoltaic panels, a hydrogen storage tank, a fire wall to mitigate potential flammability hazards associated with hydrogen, a rack containing three fuel cells, a water purification system, and a reverse osmosis system. Additionally, the facility also includes two racks with four electrolyzers and a hydrogen purification unit each. Auxiliary systems such as a water storage tank and a battery bank will be located outside of the container to complement the P3H2V plant.

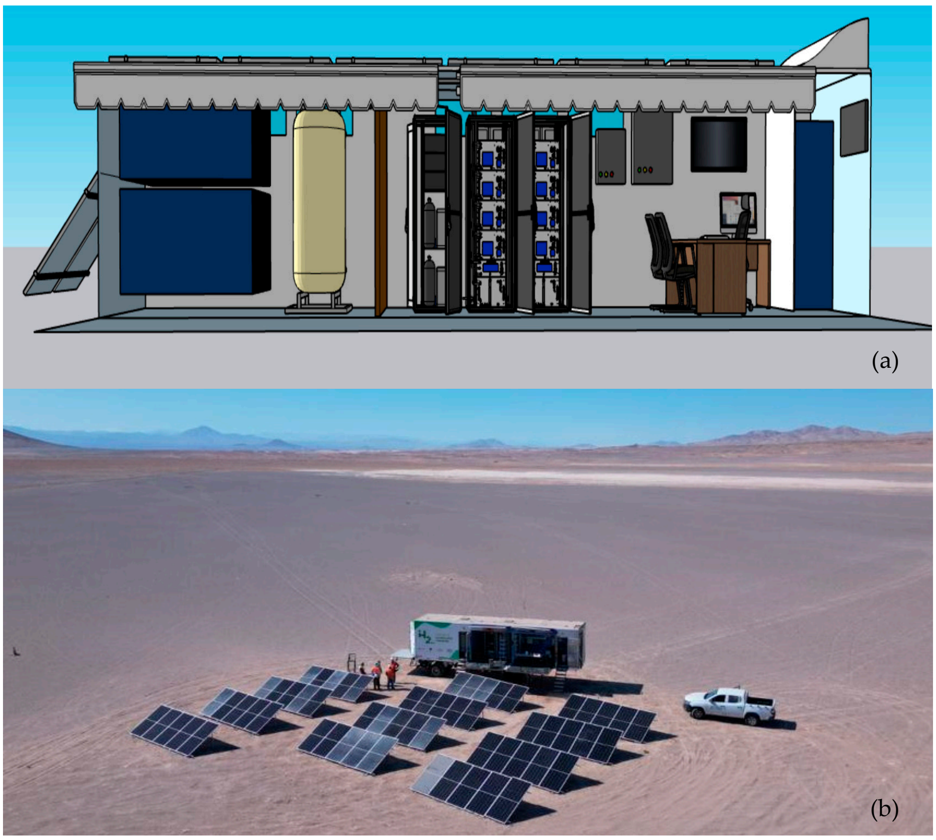


**Figure 5.** (**a**) Schematic representation of the Green Hydrogen Mobile Pilot Plant (Planta Piloto Móvil de Hidrógeno Verde, P3H2V) (**b**) Photograph of P3H2V conducting measurements in the Atacama Desert.

The production of GH with the P3HV plant is expected to yield a daily output ranging from 2.0 to 2.5 kg $H_2$. The operation of the P3HV system is composed by three primary subsystems, illustrated in the flowchart shown in Figure 6. Firstly, the photovoltaic panels, with a total installed power of 31.8 kW, are set at the beginning of each measurement "campaign" for photovoltaic energy generation. 27.2 kW of them are allocated for the electrolyzers in the hydrogen production system, and 5.4 kW are used for the auxiliary equipment of the plant. The production of $H_2$ by electrolyzers is the second subsystem, which uses water fed from the WTM-01 tank. The water in the tank has been conditioned beforehand in the reverse osmosis and deionization units, to decrease its electrical conductivity to 20 mS/cm or less (tolerance accepted by electrolyzers). The production system comprises eight anion exchange membrane (AEM) electrolyzers with a total installed capacity of 20 kW, marked EZ-01 to EZ-08. In them, the water is dissociated into hydrogen and oxygen inside of two separate chambers. While sunlight is available, the electrolyzers are powered by the photovoltaic panels. The $H_2$ produced contains a small fraction of water vapor, so that, it is sent to $H_2$ dryer-type purifiers, HPS-01 and HPS-02. This achieves a purity level of 99.999% because water is the main impurity the outcome from the electrolyzers of the facility. The $H_2$ is then stored in a type IV tank at 35 bar pf pressure or used directly in the fuel cell bank. The $O_2$ produced in the process is vented out of the container. Lastly, the $H_2$ fuel cells for power generation constitute the third subsystem. It is composed of proton exchange membrane (PEM) fuel cell bank, FC-01, FC-02, and FC-03, totalizing a maximum capacity of 3.3 kWp. The fuel cells are fed by $H_2$ coming from either the production system or from $H_2$ storage area, through compressors integrated inside the fuel cells. The subsystems enable a catalytic electrochemical reaction that generates useful electricity, which can be either stored in a battery bank or used as backup power to power the electrolyzers with electricity when solar radiation is intermittent, as well as for the plant's utilities such as lighting, screen, and computers, among others.

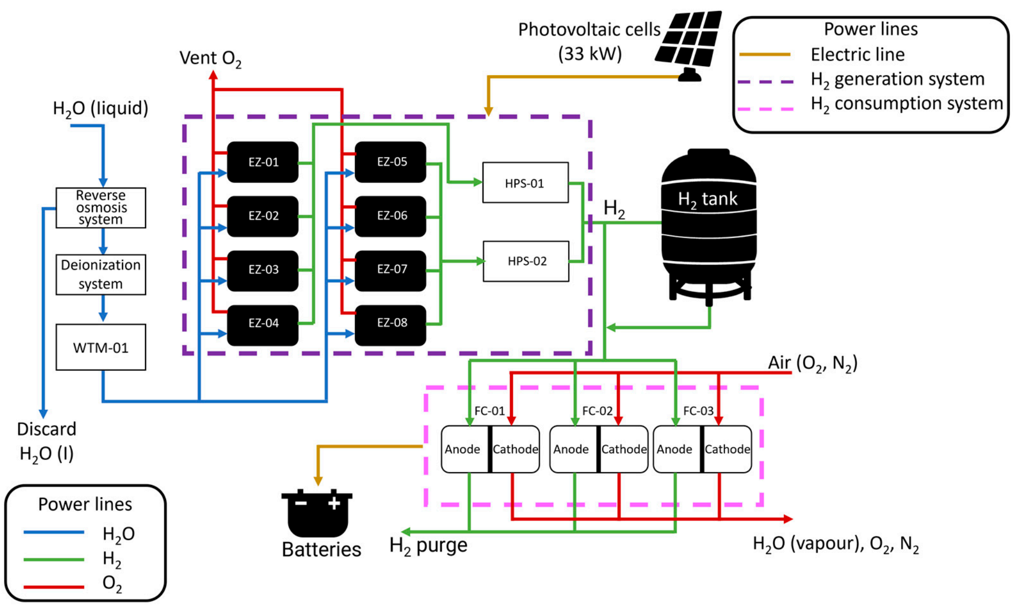


**Figure 6.** Simplified Flowsheet of Green Hydrogen Mobile Pilot Plant (Planta Piloto Portable de Hidrógeno Verde, P3H2V).

The P3H2V facility operates by supplying solar electric power and desalinated water to the electrolyzers during daylight hours, resulting in the production of $H_2$, which is then stored in a type IV gaseous storage tank. During periods of limited solar resources, such as in the afternoons and nights, or when the performance of the electrolyzers drops significantly, the fuel cells are activated to generate electricity. This innovative approach enables the P3H2V facility to leverage the surplus of solar energy for the generation of electrical power, thereby achieving sustainable and efficient energy production and management.

The sampling campaign will consist of a minimum of 16 selected points (See Figure 7), which will be chosen based on their scientific and technological interest, utilizing the methodological criteria described below. Table 3 provides a detailed outline of the experimental design and georeferencing of the sites. The sampling campaign was designed based on several criteria, including:

1. Distance between points: A maximum of 100 km between consecutive points has been set.
2. Altitude variation: The campaign will prioritize validation at different altitudes up to those relevant to the mining industry (~4000 m above sea level) in order to obtain data of the sensitivity of the PEM Fuel Cell to altitude.
3. Solar irradiation: The Antofagasta Region has favorable irradiation conditions, but local topography may affect the performance of photovoltaic panels. Thus, this factor has been considered as well.
4. Logistics: Diverse factors, including proximity to roads, terrain inclination, topographical flatness of the terrain, availability of municipal permits, access for transport trucks, and the public or private nature of the domain.


**Figure 7.** Map of P3H2V monitoring campaign (approximation).

**Table 3.** Georeferencing of the initial proposal for the P3H2V sampling campaign showed in Figure 7.

| Location | | Latitude | Longitude |
|---|---|---|---|
| 1 | Ollagüe | 21°13′2.40″ S | 68°14′28.82″ W |
| 2 | Quillagua | 21°42′17.49″ S | 69°32′0.05″ W |
| 3 | Barriles | 22°9′58.77″ S | 70°1′7.65″ W |
| 4 | Calama | 22°26′3.76″ S | 68°51′31.52″ W |
| 5 | Pass Jama/ALMA Observatory | 23°13′38.25″ S | 67°5′50.34″ W |
| 6 | San Pedro de Atacama | 22°54′48.35″ S | 68°10′59.52″ W |
| 7 | Sierra Gorda | 22°53′3.16″ S | 69°18′44.53″ W |
| 8 | Michilla | 22°42′6.80″ S | 70°16′25.29″ W |
| 9 | Peine | 23°39′53.88″ S | 68°4′19.07″ W |
| 10 | Mine Gabriela Mistral | 23°29′24.76″ S | 68°48′55.43″ W |
| 11 | Baquedano | 23°33′53.08″ S | 70°14′34.97″ W |
| 12 | Mine Zaldívar/Escondida | 24°13′57.79″ S | 69°0′6.23″ W |
| 13 | PSDA Antofagasta | 24°5′24.14″ S | 69°55′44.29″ W |
| 14 | Pan American Highway North, Route 5 | 24°29′48.43″ S | 69°50′31.43″ W |
| 15 | Paranal Observatory | 24°43′46.03″ S | 70°21′49.35″ W |
| 16 | Taltal | 25°34′7.19″ S | 70°21′51.00″ W |

By taking these factors into account for the design of the sampling campaign, it is expected to collect data that will contribute significant scientific and technical value.

## 3. Future and Perspectives

Data from the preliminary analysis (five-day campaign) shows that a generation of the theoretical total of 2.8 kg/day-$H_2$ is achievable, but in the first point of campaign, only an average of 1.8 kg has been achieved of $H_2$ generated. The reduction in daily energy generation can be attributed to the soiling of the photovoltaic and the high temperature of the panels, which negatively impacts overall efficiency. Calculations indicate that the peak capacity is attained for five hours of the day, with a notable decline in power output observed during the afternoon. These findings highlight the relevance of addressing panel soiling to optimize energy production and guarantee consistent and reliable electrical output. Further research and development in this area may result in solutions for improving the performance and longevity of photovoltaic systems.

Assessing parameters such as: Electrolyzers efficiency, hydrogen storage issues, and fuel cell utilization hold significant importance within the field of hydrogen generation, as the accurate measurement of these parameters is crucial in determining the overall efficiency of the process. In addition, the impact of seasons and day/night on photovoltaic power will be considered when generating this map. Therefore, a rigorous analysis of the measured parameters will be conducted to exclude any potential errors and establish potential of hydrogen generation in the Antofagasta region in an empirical basis and realistic conditions. The comprehensive mapping campaigns and the data obtained will be useful to develop a simulation-based regional map. The map will enable the identification of strategic points within the region that has the highest production efficiency. The simulation-based approach provides a more advanced and precise depiction of the hydrogen generation system, which enables the identification of potential bottlenecks and opportunities for optimization.

This project aims to provide a comprehensive understanding of the key factors influencing the efficiency of hydrogen production, storage, and utilization. The forthcoming publication of the full map of GH production under realistic field conditions by the end of this year is anticipated to significantly contribute to this endeavour. The growth of the GH energy industry presents various challenges that necessitate careful attention and proactive measures. These challenges include the requirement for large-scale technological industrialization, substantial investments, and coordinated efforts to meet the increasing demand for GH. Furthermore, there is an urgent need to cultivate a skilled talent pool proficient in electrolysis, hydrogen storage, fuel cell technology, and system integration. Overcoming these challenges calls for continuous research and development initiatives to drive innovation and surmount technical limitations. Collaborative actions involving governments, industry stakeholders, and research institutions are essential for overcoming these challenges and fostering a resilient and sustainable hydrogen economy.

The insights derived from this study hold immense value for policymakers and stakeholders in the energy sector and industry, offering essential information to guide decision-making processes and strategic planning. While economic considerations are not the primary focus of this project, the findings and knowledge generated will contribute to a more comprehensive understanding of the technical aspects and potential applications of hydrogen in the region. This understanding can inform future economic assessments and decision-making processes, enabling a more informed and strategic approach to the development of hydrogen-related projects in the area. With the anticipated publication of the full map of GH production under realistic field conditions by the end of this year, stakeholders will have access to comprehensive data and analysis that can inform and support their efforts in advancing the hydrogen economy.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16114509/s1, Table S1: With a list of projects currently declared under construction in 2021all Under going energy projects in Chile 2021. This list was used to plot the Figure 1.

**Author Contributions:** Conceptualization, supervision, funding acquisition and researching L.M.; writing—original draft preparation, E.C.-A. and A.C.-A. based on inputs from L.M.; writing—review and editing, E.C.-A., I.C. and A.C.-A.; data acquisition J.S., N.S. and F.H.; PV advisor S.R. All authors have read and agreed to the published version of the manuscript.

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