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PAVING THE ROAD FOR COMPETITIVE GREEN HYDROGEN HUBS: DOES CHILE HAVE A CHANCE?

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May 2023

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https://doi.org/10.25613/42F2-EW17

Executive Summary

Chile's economy decarbonization process is underway. The country has no hydrocarbon reserves and has limited hydro resources. It has historically relied on imported oil, natural gas, and coal to meet its energy needs. However, its Atacama Desert has the best solar radiation in the world while the extreme south has the strongest wind onshore. As a result, Chile already generates more than 20% of its electricity using solar and wind power. In this context pursuing the production of green hydrogen using renewable electricity resources has been embraced by the government and in 2020 issued "The National Green Hydrogen Strategy of Chile" which has both a medium- and a long-term vision.

This strategy relies on the abundance of renewable resources and ample private sector participation: Concentrated solar power, solar photovoltaic, on-shore wind and run-of-river, may allow Chile to produce the cheapest green hydrogen on the planet once the technology, infrastructure and regulatory challenges are taken care of — including financing and acceptance by the community at large.

The technology is currently being tested with multiple pilot projects with public and private funding to provide incentives for the production, delivery, and use of green hydrogen. They are expected to be fully tested by 2025 for local consumption, with the first phase providing:

- Green hydrogen to replace the gray hydrogen — from hydrocarbon processes that emit CO2 — currently used by refineries and the chemical, cement, and steel industries.
- Derivatives of green hydrogen such as methanol to replace diesel in heavy-duty transportation in mining activities, and in long-distance transportation via buses, trains, and heavy-duty trucks.
- Green ammonia to produce explosives and fertilizers.

A large part of the challenge in scaling up the production of this new fuel for the local and international market is the development of a regulatory framework that provides certainty and transparency for its whole value chain. Green hydrogen production, storage, transportation and distribution, and end users need reliable rules for the investors, operators, consumers, and communities surrounding these facilities. To incentivize reducing emissions and local demand of renewables including green hydrogen, Chile already has a carbon tax of $5.00/ton of carbon dioxide which the government is planning to increase to $35.00/ton of carbon emissions.

A new law on energy efficiency (Law 21.305) has now defined "green hydrogen" as a fuel, rather than the previous definition — "a dangerous extremely flammable element" — that was used when green hydrogen was regulated by the Health Ministry. In addition, Law 21.505, approved November 2022, included hydrogen storage to be used as a backup for the electric system, to manage the intermittency of renewable power generation. As a result, the Ministry of Energy is the entity responsible for this new fuel and its strategy implementation.

It has designed a calendar with three phases with the purpose to adapt existing regulations and design new ones to facilitate the development of this new energy vector:

First Phase 2020-2023 to elaborate the rules to make green hydrogen, its specifications and delivery.

Second Phase 2024-2027 to prepare the rules for hydrogen transport by pipeline networks, technical and safety requirements in coordination with the Ministries of Transportation and Mining.

Third Phase 2028 forward to prepare regulations for handling hydrogen in port facilities in conjunction with the Ministries of Transportation and Defense.

One critical objective is to have an efficient and simplified regulatory framework where the operators can benefit from submitting their project environmental requirements to one agency; the "one window concept," through which all required permits would be handled with the pertinent agencies in an expeditious manner.

Financing is available from multilateral and international organizations as well as the government which has provided grants to industry participants with pilot projects. Memorandums of Understanding (MOUs) for technical, financial, and commercial support have been signed with international agencies and organizations around the world. At the same time Chile has developed the mechanisms for consultation with local communities about the impacts they may experience due to the location of these plants and the use of renewable energy sources.

Chile's northern region has already developed competitive solar generation, and desalinization plants, and has a vibrant mining sector with the national copper company Codelco and multiple private operators. This environment is promising for the development of a green hydrogen ecosystem. As highlighted in this report this region already has multiple pilot projects in various phases. Hydrogen exports could start with ammonia, for which ships are available, and later include liquid green hydrogen once technical, safety, and cost issues are resolved.

Given the progress it has made on incorporating renewables into its energy matrix, Chile is on the way to meeting its climate goals— but the urgency to develop green hydrogen to further reduce carbon emissions in mining operations, heavy-duty and long-distance transportation, and agriculture, remains.

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Introduction

As part of global efforts to achieve net-zero emissions[1] by 2050 (IEA 2021a), green hydrogen has emerged in recent years as a promising fuel. Green hydrogen — hydrogen generated by electrolysis from water powered by renewable sources rather than processes using fossil fuel energy sources — has the potential to disrupt fossil fuel energy markets and reduce emissions in many sectors: Green hydrogen can address hard-to-decarbonize sectors in which electrification is not an economic option. In 2020, agriculture and energy (including transportation, industrial, and electricity use) together accounted for over 90% of the world's greenhouse gas emissions (agriculture's share was 18.9% and energy's 73.2%).[2] South America accounts for just 2.9% of global carbon emissions,[3] but with the cleanest energy matrix[4] of any region worldwide (Elizondo-Azuela et al. 2017) and a wealth of renewable energy resources, particularly in Chile, this region has the potential to become a leader in the green hydrogen economy.

Indeed, Chile was the first country in Latin America to publish its National Green Hydrogen Strategy. It has already initiated several green hydrogen pilot projects, capitalizing on the sun in northern Chile and the wind resources in the south, which are some of the cheapest and most abundant in the world. Its comparative advantage extends also to existing infrastructure — including ports, roads and railroads — plus mining operations that could provide a new source of demand for hydrogen, particularly in the Antofagasta Region.

Green hydrogen is emerging as an energy option to be included in the country energy matrix. The potential demand, nationally and internationally for this new fuel is considered in this report. Large-scale consumers of green hydrogen include industries where hydrogen is already used, such as ammonia production, as well as mining and heavy transportation where hydrogen derivatives could replace existing fuel sources and where batteries may not be an economic option.

In this report, we discuss the opportunities and challenges involved developing a hydrogen industry in Chile, with particular focus on hydrogen projects using solar photovoltaic power. A great opportunity to highlight in Chile is the national commitment and government support to develop this hydrogen industry, as well as the favorable global conditions with increased funding available to develop clean hydrogen projects as well as the demand that could potentially be satisfied by green hydrogen from Chile. Some challenges identified and discussed in this report are:

- Technical challenges associated with existing and evolving different hydrogen electrolyzer technologies to be adopted.
- Economic and social complexities include project financing opportunities, supportive government policies and a robust regulatory framework, developing a competitive market, and maximizing community benefits.
- Securing access to economical and sustainable renewable energy sources in the medium to long term.

- Developing and/or upgrading the infrastructure required for local and international transport and storage of hydrogen.
- Developing the use of hydrogen derivatives as a fuel, and the corresponding local and international infrastructure to meet demand.

The first section of this report reviews the importance of hydrogen as an alternative to face climate challenges and the economy's decarbonization. It also discusses concepts of the production and demand of hydrogen, reviews the supply chain and technical challenges associated with electrolyzers. The second section presents Chile's comparative advantages to lead the green hydrogen market development, and it discusses the current opportunities for doing so. The next section discusses the advantages of Antofagasta as a Hydrogen hub, and the Chilean regulatory framework is briefly presented in the following section. We discuss the potential challenges to market development in the fifth section, and concluding remarks are presented in the last section.

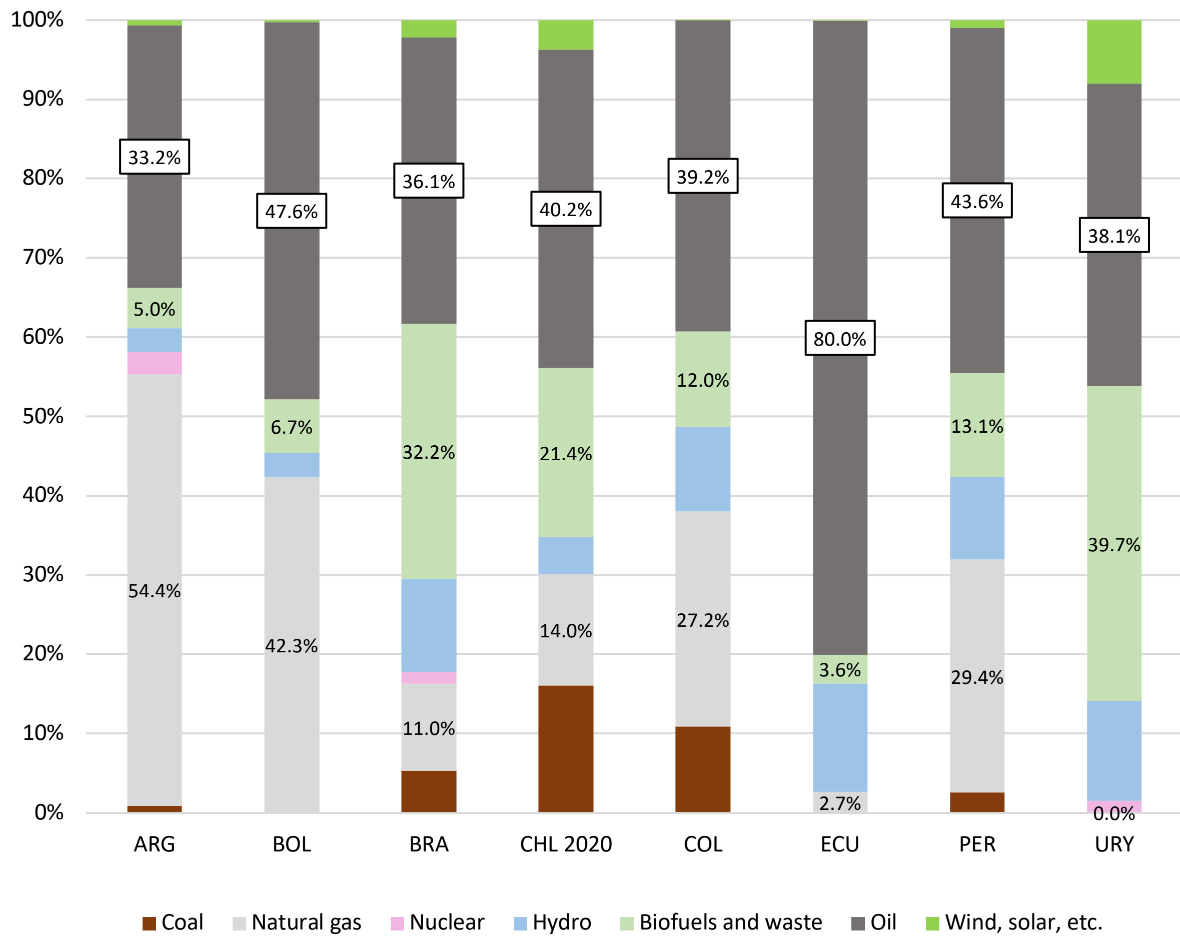
Why Hydrogen?

Environmental Goals: Mitigating Climate Change?

Over the past few decades, climate change has emerged as an international topic of concern, debate, and policy intervention. In 2000, the United Nations named climate change as its seventh Millennium Development Goal and in 2015 as one of its 10 Sustainable Development Goals. In December 2015 the Paris Agreement, a legally binding international treaty to reduce emissions, set the ambitious target of limiting global temperature rise to 1.5°C or, at most, 2°C.[5] Currently 194 parties (193 countries and the European Union) have joined the Paris Agreement. As part of the agreement, developed countries agreed to jointly invest US$ 100 million per year in climate finance initiatives such as the U.N.'s Green Climate Fund by 2020, and to continue this level of annual spending through 2025.

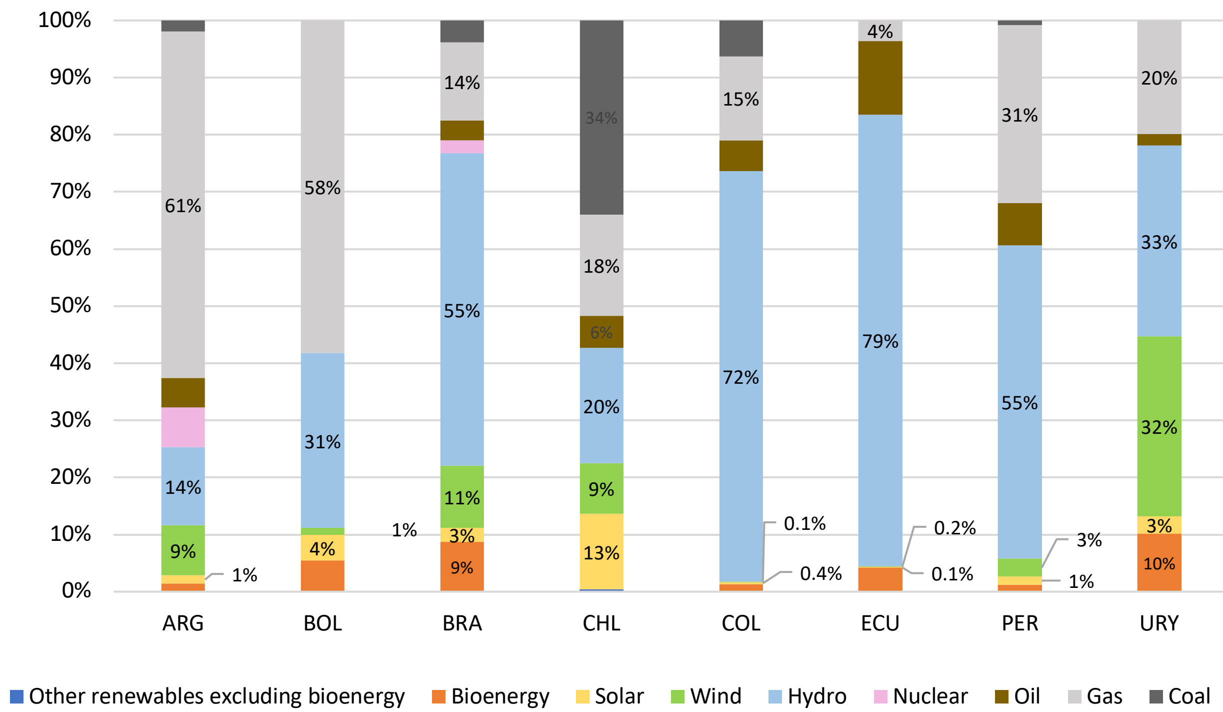
Spurred by widespread political support and investment, solar and wind power generation have expanded significantly — particularly since 2010, when access to funding, policy incentives, and technological advances began to make these technologies economically competitive with fossil fuels. In 2021, a record 295 gigawatts (GW) of new renewable power capacity came online, driven partly by supportive policies in China, the European Union, and Latin America (IEA 2022d).[6] Thus the worldwide average, by 2021, of the electricity generated from wind and solar power was above 10%; but South American countries like Uruguay, Chile and Brazil are already above those levels with 35%, 22% and 14% respectively (see Figures 1 and 2).

Figure 1. Total Energy Supply Composition by Source by Country (2019)



Source: EIA dataset and Our World in Data Based on BP Statistical Review of World Energy 2022 and Ember Yearly Electricity Data 2023.

Figure 2. Electricity Generation Composition by Source (2021)



Source: EIA dataset and Our World in Data Based on BP Statistical Review of World Energy 2022 and Ember Yearly Electricity Data 2023.

Achieving high levels of renewable energy penetration on the electricity grid, however, has been made more difficult by the intermittency of solar and wind generation, which reduces grid reliability and security for electricity users. In addition, major sectors like transport — especially trucks and other heavy-duty equipment — and industry are hard to electrify and so have remained highly reliant on fossil fuels.

As the lightest element on earth, hydrogen is highly flammable, and its combustion only generates water vapor. Due to its versatile properties as an energy vector, green hydrogen — produced from water in a process using renewable power — has emerged as a promising option to address the above challenges:[7]

- It can mitigate the intermittency of renewable electricity by storing energy for power plants to use when sun and wind resources are not available.
- It can be used as a fuel to decarbonize hard-to-abate sectors such as mining and heavy-duty transport where using batteries is not an economic option to back out hydrocarbon fuels, and industries that require high-heat processes where electrification is neither economically nor technically viable.
- It can also help to reduce emissions in the agriculture sector if used as an input for ammonia, a key ingredient in fertilizer that has traditionally been produced from brown and gray hydrogen (which are derived from fossil fuels that emit CO2).

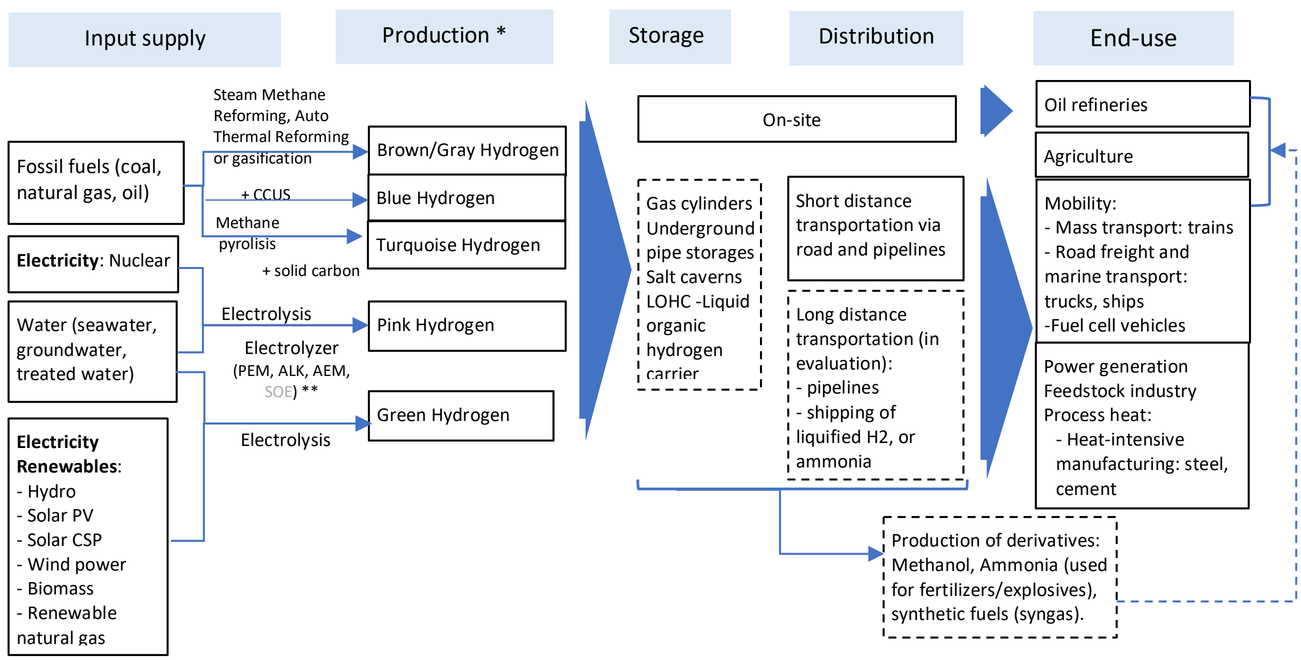
Hydrogen Production and Demand

Current Production and Consumption. Hydrogen has been produced and used for decades. As of 2020, global hydrogen production and consumption amounted to over 90 million tons (Mt) annually. The majority (96%) of this hydrogen is produced by steam-reforming hydrocarbons like methane, lignite, and oils (IEA 2021b). These processes can generate large quantities of hydrogen at comparatively low costs but have a substantial carbon dioxide (CO2) footprint (about 900 million tons in 2021) (ESMAP 2020b; IEA 2022b).

Water electrolysis, using electricity to split water molecules into hydrogen and oxygen, offers an alternative method to produce hydrogen. If powered by renewable energy sources such as wind or solar energy, this hydrogen is produced with zero CO2 emissions and can be considered “green.” However, in 2021 less than 0.04% of pure hydrogen was produced using water electrolysis and renewable energy (IEA 2022b; IRENA 2020).

One of the most promising short-term potential applications of green hydrogen is to replace the brown and gray hydrogen (produced from hydrocarbons) already used by industries such as agriculture and petroleum. Currently hydrogen is not internationally traded like other commodities. Indeed, 64% of the 90 million tons of hydrogen produced in 2020 was produced and consumed on-site. Most hydrogen (78%) is used to make ammonia for chemical or oil refining feedstocks. Hydrogen is also used in the production of explosives and petrochemicals (also from ammonia production), chemical and synthetic fuels, and, in smaller amounts, iron (as an input for direct reduced iron, or DRI) and steel production (IEA 2021c; see hydrogen value chain in Figure 3). Hydrogen in South America is primarily used by oil refineries, the ammonia-based fertilizer industry, and to produce methanol. Brazil and Argentina had the largest demand (0.4 million tons each by 2019), followed by Chile and Colombia (0.2 million tons each by 2019) (IEA, 2021b).

Figure 3. Supply Chain of Hydrogen



Notes: (*)
1) Brown and gray hydrogen are extracted from fossil fuels via steam reforming with no treatment of the carbon emissions produced.
2) Blue hydrogen is extracted from natural gas via steam methane reformation and includes capture and storage of carbon emissions.
3) Turquoise hydrogen is obtained from fossil fuels by methane pyrolysis, producing solid carbon and no CO_2 emissions, with no need for carbon capture and storage.
4) Pink and green hydrogen are extracted from splitting the water molecule through electrolysis using, respectively, nuclear and renewable energy sources.
(**) PEM = polymer electrolyte membrane; AEM = anion exchange membrane, and SOE = solid oxide electrolyzer.

Source: Diagram created by the authors.

While the feasibility of green hydrogen depends on a variety of factors, there are two significant barriers to its large-scale production: 1) the current high cost of producing green hydrogen relative to current hydrocarbon-based technology options and 2) the cost and complexity of hydrogen storage and transport, which requires either retrofitting existing equipment or building new infrastructure to accommodate hydrogen's unique characteristics.

Green Hydrogen Needs To Be Economically Competitive with Fossil Fuels. This would require the cost of green hydrogen, which currently fluctuates between US$5 and US$9/kg (Mac Dowell 2021), to be lower than US$2/kg (equivalent to US$50/MWh) (see Table 4 in the Appendix).[8] Costs can be reduced by having access to low-cost renewable energy and by improving the efficiency and affordability of electrolyzers.

- When sourced from solar photovoltaic energy (PV) — currently one of the lowest-cost and most readily scalable renewable energy sources — electricity accounts for 60%-70% of the total cost of green hydrogen projects (Patonia and Poudineh 2022a).[9] The cost of electricity in green hydrogen-solar PV projects, however, may vary depending on whether a project sources energy from a dedicated solar power installation or contractually from the grid via a power purchase agreement (PPA).
- Electrolyzers, on the other hand, account for about 20% of the total cost of hydrogen projects (Patonia and Poudineh 2022a). There are four leading electrolyzer technologies, each with distinct advantages and drawbacks: alkaline (AEL), polymer electrolyte membrane (PEM), anion exchange membrane (AEM), and solid oxide electrolyzers (SOE) (IRENA 2020; Patonia and Poudineh 2022a). The first two are already commercialized, and the third is in a market testing stage, with promising initial results. The fourth, SOE, is still at an early stage of development.
  Each type of electrolyzer technology has different technical properties (see Table 5 in the Appendix) and entails distinct advantages and disadvantages in terms of materials required, environmental impacts, and efficiency (see Table 6 in the Appendix). Low temperature electrolyzers (PEM, AEM and AEL) have the most potential for rapid, large-scale deployment; from these AEM and PEM are the best electrolyzers for minimizing safety issues (such as water condensation), while producing high purity hydrogen: Both produce hydrogen with a purity greater than 99.99% (Santos et al. 2021). PEM technology has been found to be the most suitable for intermittent renewable energy sources but tends to be more costly due to the use of scarce catalysts (platinum and iridium).[10] AEM uses less expensive catalysts such as nickel and is thus slightly cheaper than PEM technology.

In addition to electrolyzers, several other system components contribute to the capital expenditures required for green hydrogen generation, which should be accounted for best efficiency. These include:

1. rectifiers or power transformers that allow converting alternating to direct current;
2. water purification units that are required to guarantee purified feed water with low conductivity (up to 1 microsiemens per centimenter μS/cm) to avoid any damage to the electrolyzers;
3. cooling systems needed to dissipate the heat generated across the stages of green hydrogen production may add to electricity usage — industrial cooling machines and/or cost-effective dry coolers are often used to lower the temperature of product gases to 10°C (near ambient temperature); and
4. compressors, required to allow for optimal storage and transport of hydrogen by compressing hydrogen to a final pressure that varies from 80 to 900 bars depending

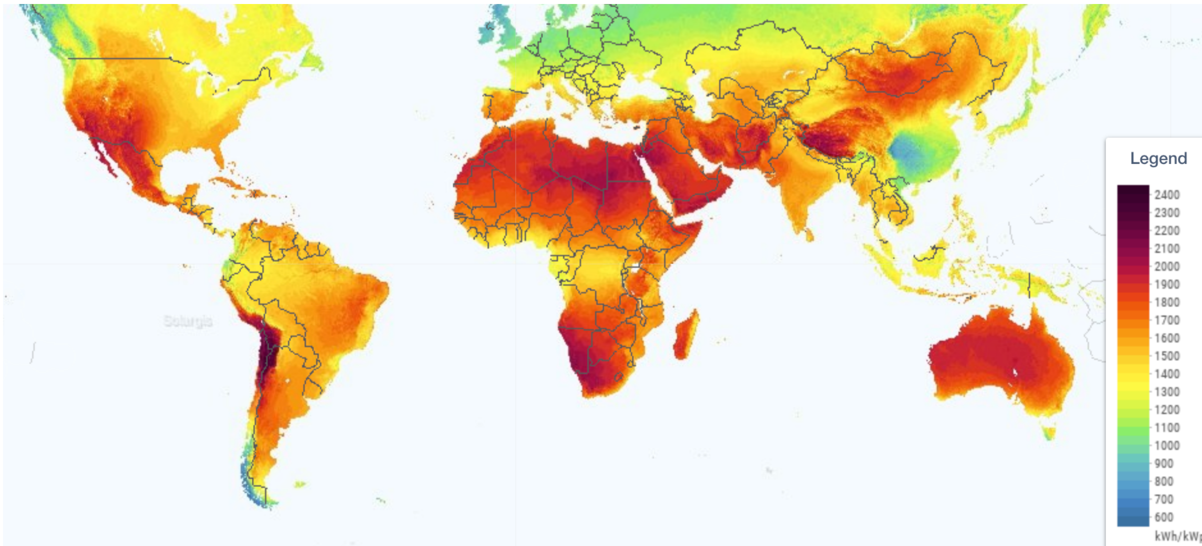
on the application — pipeline injection, ammonia production, etc. — (see Table 7 in the Appendix) (Holst et al., 2021).

Transport of Hydrogen Presents Both Technical and Economic Challenges. Hydrogen is a very flammable element, and it is colorless and odorless when combusted; its flame tends to be invisible in daylight. Being the lightest of the elements, it also can leak very easily. In order to store and transport it, hydrogen conditioning — changing its physical condition but keeping its chemical properties — is required: keeping it in a gaseous state through pressurization (lowering its pressure) and then changing it to a liquid state via liquefaction or cryo-compression (Clarke et al. 2022; SEA 2023). According to SEA (2023), storing gaseous hydrogen in pressurized tanks (between 350 and 700 bars) is the most mature technology. So, hydrogen can be transported by pipeline, truck, or ship, in various forms including gaseous hydrogen, liquid hydrogen, and as derivatives such as petrochemicals, ammonia, methanol, and alkalines/oleofins. Various companies and governments are pursuing a variety of transportation strategies; for instance, the world's first shipment of liquid hydrogen from Australia to Japan took place in May 2022.

All types of hydrogen and its derivatives need specialized infrastructure to ensure safe and reliable delivery to end users. For export, the ports handling shipping and delivery must have suitable depth, facilities, and safety standards. Building the appropriate facilities for conversion and reconversion, obtaining the capital to make these changes, and generating demand for what will likely be a higher-cost product may not make economic sense. Using green ammonia for fertilizers and for explosives rather than reconverting it to hydrogen can, however, reduce some of the costs associated with import. For most, liquid ammonia will likely provide the most effective long-distance green hydrogen carrier in the short term, because the infrastructure to transport ammonia already exists (Patonia and Poudineh 2022b) and there is an existing fertilizer market for the ammonia.

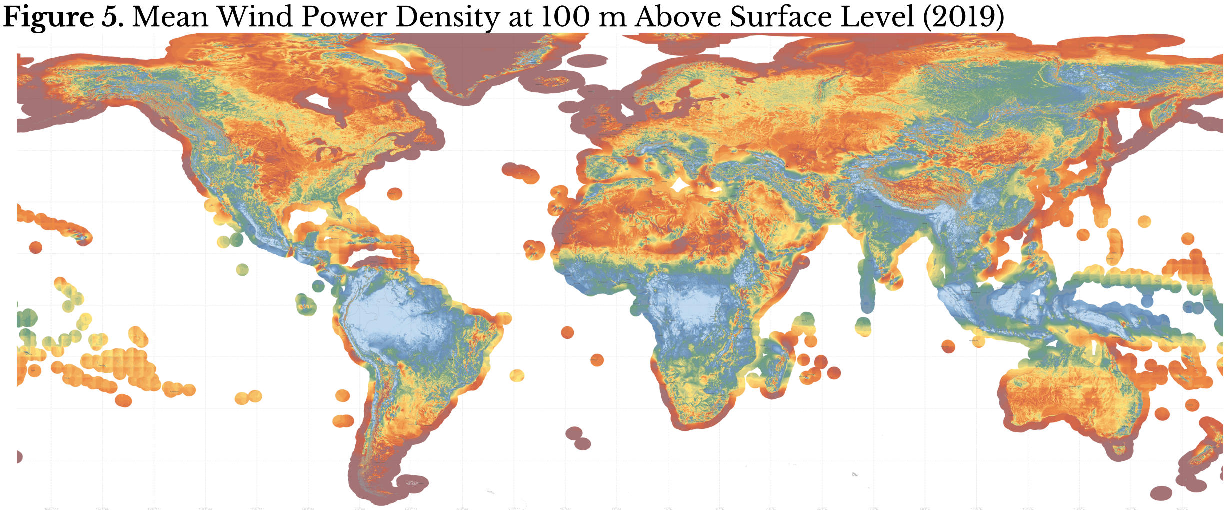
Hydrogen Potential in the Region. Access to renewable resources and being near to where there is product demand can facilitate the market development of hydrogen. Though South America's hydrogen market represents less than 3% of total demand (IEA 2021b), its abundance of renewable resources make it a promising site for developing green hydrogen. Chile, in particular, stands out as the country with highest solar and wind resources around the world (see Figures 4 and 5 below), in the northern and southern regions, respectively.

Figure 4. Photovoltaic Power Potential (2021)



Source: World Bank Group, "Global Solar Atlas:" https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country.

Figure 5. Mean Wind Power Density at 100 m Above Surface Level (2019)

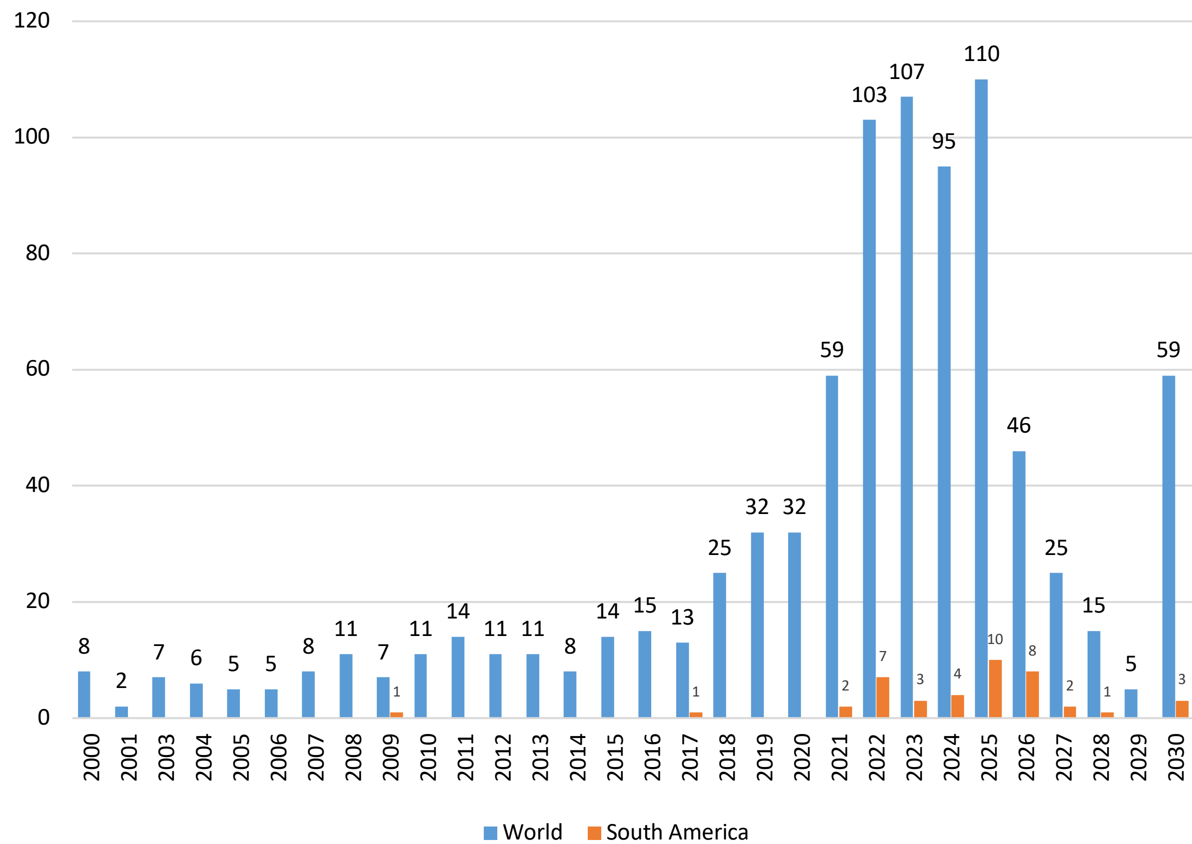


Source: The World Bank Group, "Global Wind Atlas."

Green hydrogen projects and associated innovations have already attracted investment by governments (both within South America and elsewhere), multilateral organizations, and some private investors as a means to reach decarbonization, climate and energy security goals. According to the IEA as of October 2022, 1,201 projects have been commissioned worldwide since the year 2000 to produce hydrogen and derivatives (ammonia and methanol) via electrolysis; 65 (5.4%) of these in South America (see

Figure 6). Out of these green hydrogen projects in the region, 43% are in Chile (see Figure 7).

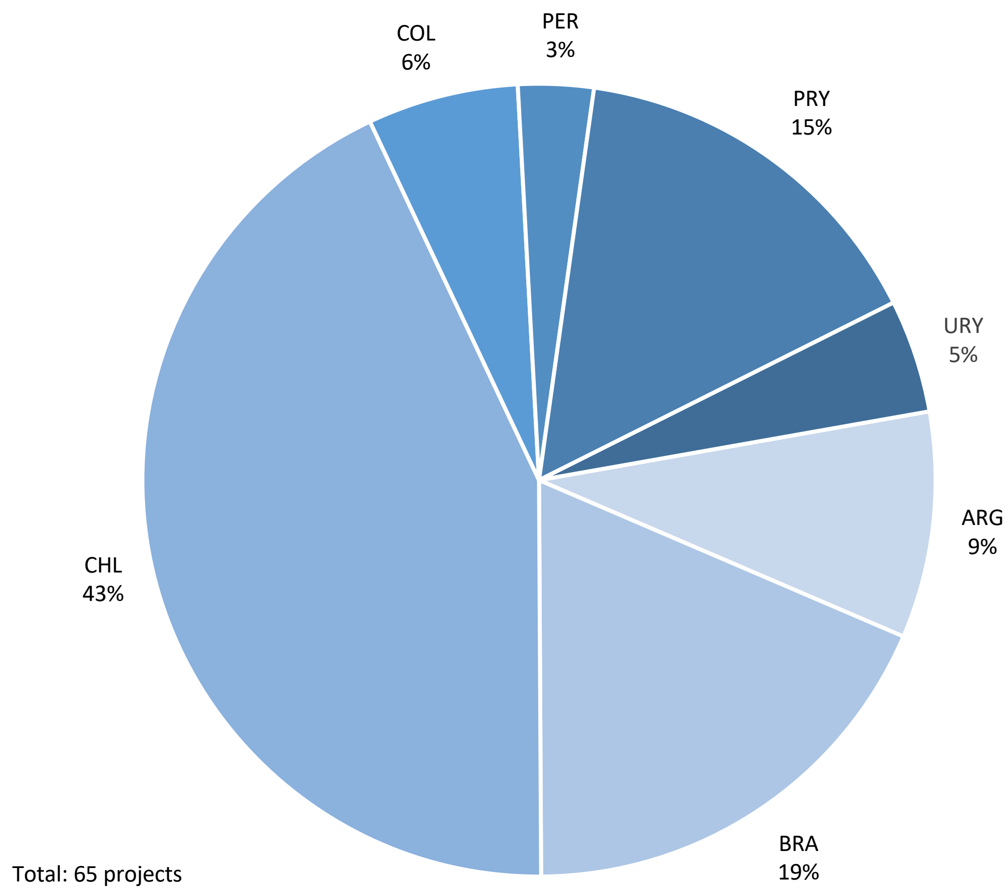
Figure 6. Number of Hydrogen Production Projects via Electrolysis Commissioned Since 2000 to 2030



Note: Project counts include all renewable energy sources in each hydrogen facility, including wind and hydropower, to produce hydrogen, ammonia, methanol and various products.

Source: IEA, Hydrogen Projects Database, 2022.

Figure 7. Share of Green Hydrogen Projects by Country in South America



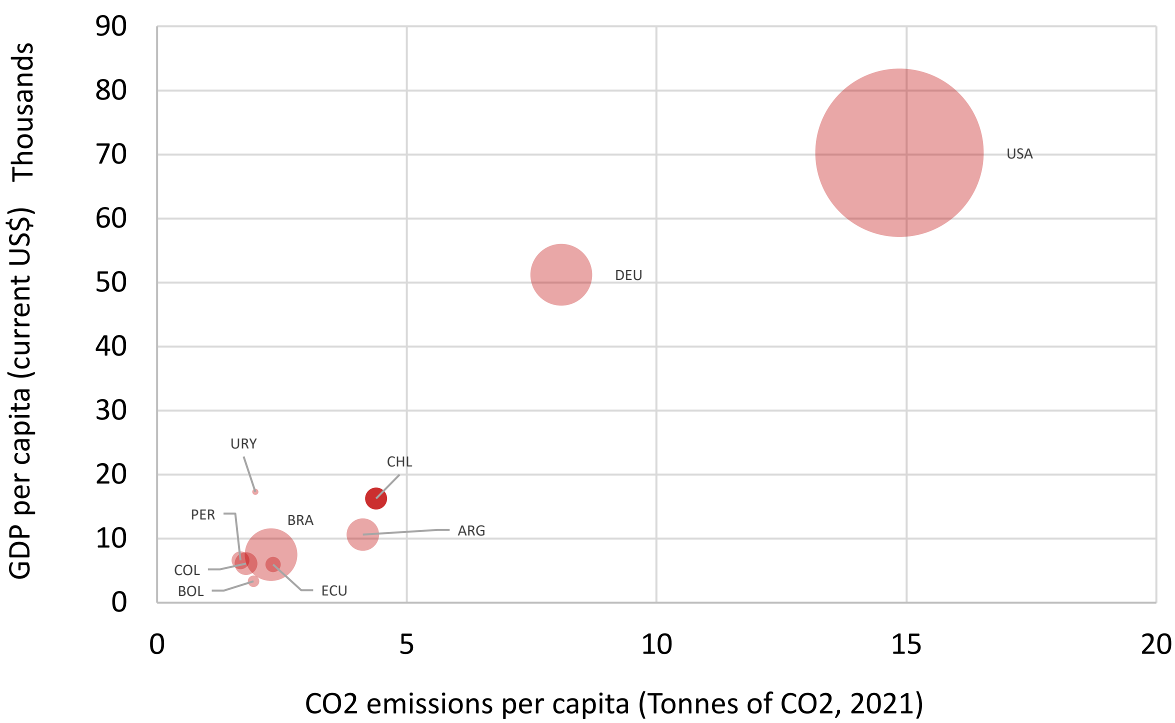
Note: Project counts include all renewable energy sources in each hydrogen facility, including wind and hydropower, to produce hydrogen, ammonia, methanol and various products.

Source: IEA, Hydrogen Projects Database, 2022.

Why Chile?

One of the most promising economies in South America, Chile was, until 2020, the only OECD member from South America. More economically advanced than its neighbors, Chile also faces higher energy needs and higher pressure to decarbonize its economy, which explains its increasing renewable sources in its energy matrix (see Figures 8 and 9). Unlike other South American countries, Chile does not have fossil fuel reserves, so it must import oil, gas, and coal to satisfy its demand.

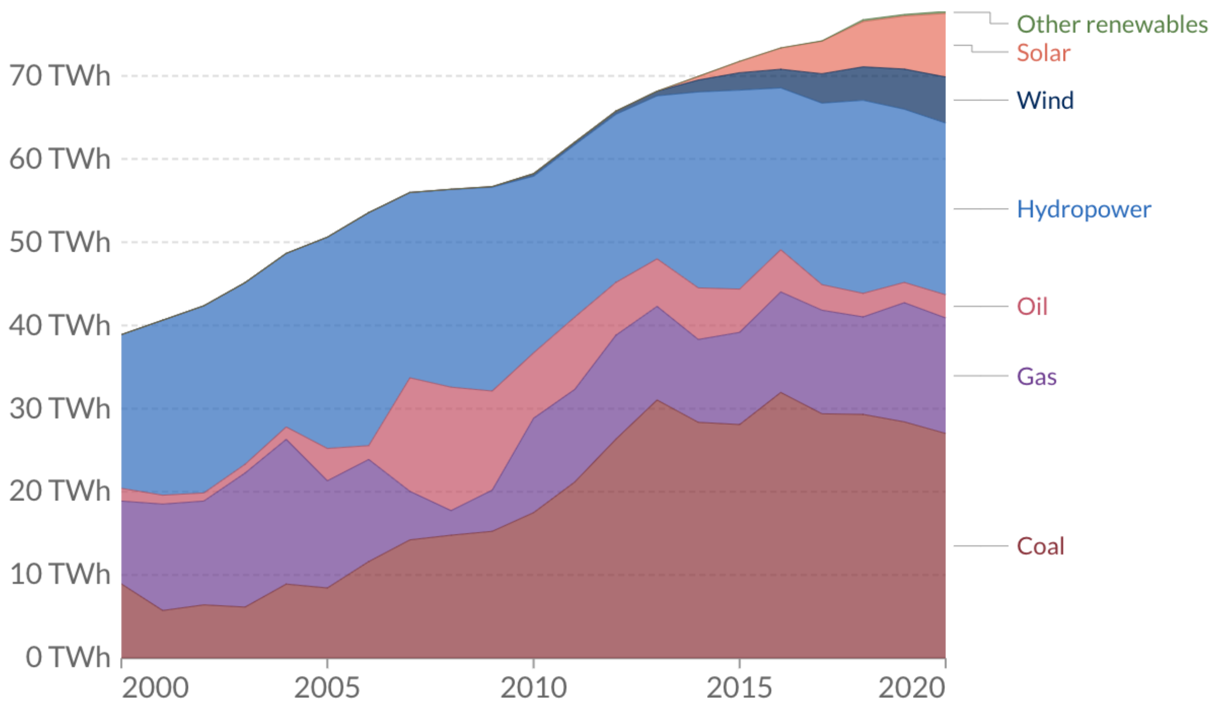
Figure 8. Emissions of CO2 and GDP per capita (2021)



Note: The size of the bubbles indicates the total annual CO2 emissions of the country.

Source: Our World in Data based on the Global Carbon Project 2022 and the World Bank Group.

Figure 9. Share of per capita greenhouse gas emissions by sector, 2019



Note: "Other renewables" includes waste, geothermal, wave and tidal.

Source: Our World in Data based on BP Statistical Review of World Energy 2022; Ember 2023.

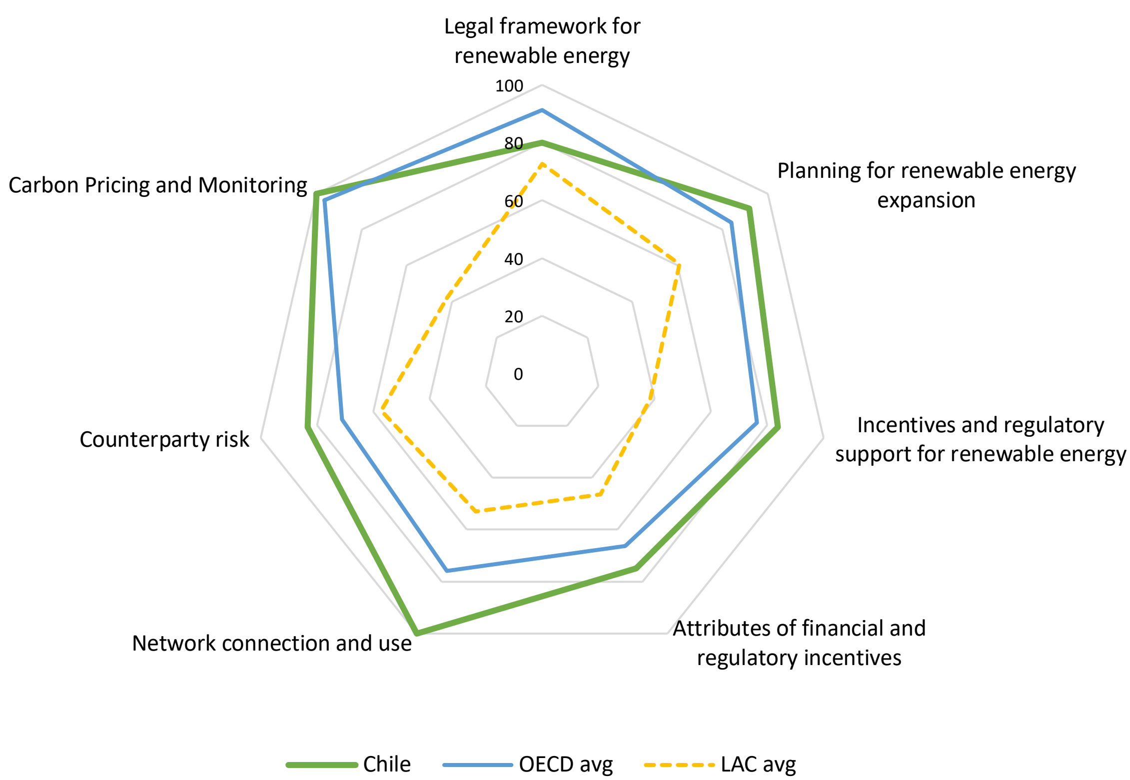
With Abundant Renewable Energy Sources, Chile Has Significantly Increased Its Participation in the Energy Matrix. Northern Chile has the highest solar radiation on the planet: the Atacama Desert has an average annual direct solar radiation of 2506 kWh/m^2, which is higher than solar radiation levels in Spain, Abu Dhabi and the U.S. (Moraga-Contreras et al. 2022). The country's southern region has high wind potential, and unlike other regions, there is no difference in wind strength on land and offshore. Wind turbines 120 meters high can reach plant capacity factors of over 60% on land, equivalent to much more expensive off-shore turbines in other countries.

Due to its abundant and high quality non-conventional renewable resources, Chile has been heavily investing to leverage its solar and wind power. In fact, its renewable energy policy has already been proved effective since the country reached its goal of having these two sources providing 20% of its power matrix by 2018, seven years earlier than the planned date of 2025 (BCNC 2022).

As shown in Figure 9, the role of non-conventional renewables in the power mix has been expanding since 2013, due to significant private investment participation and policies encouraging renewable energy. Over the past six years, Chile has increased its solar and wind energy generation capacity five-fold. If existing trends continue, up to 70% of the country's electricity capacity matrix will be sourced from renewable energies by 2030 (Ministerio de Energía de Chile, 2020).

The Country Has Developed a Suitable Investment Climate for Renewables. According to the World Bank and ESMAP's Regulatory Indicators for Sustainable Energy (RISE) score — a proxy for progress in the investment climate for investment in renewables — by 2021, Chile (with a total score of 87) outperforms the Latin American and Caribbean average (score 61) and scores even above the OECD average (score 86) (World Bank Group, 2022). Within the specific renewable energy pillar, Chile outperforms to its group's averages in most of the factors of the renewable energy, such as counterparty risk, network connection and use, attributes of financial and regulatory incentives, incentives and regulatory support for renewable energy, carbon pricing and monitoring (see Figure 10).

Figure 10. Renewable Energy Pillar 2021 — Regulatory Indicators for Sustainable Energy (RISE) Score



Source: World Bank Group, Regulatory Indicators for Sustainable Energy — RISE 2022: https://rise.esmap.org/analytics.

Chile Launched its National Green Hydrogen Strategy in 2020. In line with its renewable energy expansion and ambition, Chile published its National Green Hydrogen Strategy in November 2020 (Ministerio de Energía de Chile 2020). It set the goal of becoming a green hydrogen producer and exporter by expanding its electrolysis capacity to 5 GW by 2025 and then to 25 GW by 2030 —by which time Chile would potentially be producing the cheapest green hydrogen in the world, costing less than US$1.50/kg of H2. In the short-term the plan is to meet national hydrogen demand, while in the long-term the objective is to export hydrogen and its derivatives long distance — the global demand is likely to be many magnitudes greater than what can be used in a small market like Chile. According to its plan:

- Pre-2025, prioritized industries for hydrogen demand are oil refineries, ammonia, mining haul trucks, heavy-duty transport, long-range buses, and blending in natural gas pipelines (in proportions of up to 20%).
- Post-2025, Chile also aims to develop applications and uses of ammonia as shipping fuel and synfuels usage in aviation.

Local demand for hydrogen would come primarily from large-scale consumers such as mining, steel manufacturing, and cement companies; heavy-duty and long-distance transportation; and ammonia for use in fertilizers and explosives.

Chile's National Green Hydrogen Strategy (Ministerio de Energía de Chile 2020) helped create a roadmap to develop this industry, laying out a set of clear objectives to guide green hydrogen planning and projects. Guided by this framework, representatives in the public and private sector are currently working and advocating to develop more concrete and specific policies around topics such as crafting clear regulatory signals and developing avenues for financial support such as tax incentives under an "action plan." This plan addresses four types of policy:

- **Policies to promote domestic and export markets** by 1) making available public funding to support green hydrogen projects, 2) fostering private-public discussion to improve carbon price and tax policies that better capture the negative externalities of fossil fuels so as to spur switching to hydrogen as a fuel, and 3) deploying a green hydrogen diplomacy to internationally position Chile as a source of exportable clean energy carriers.
- **Policies about standards, safety and piloting** to provide regulations to reduce investors' uncertainty and risk by 1) developing a regulatory framework to ensure safety standards throughout the hydrogen value chain, 2) coordinating a framework to ease permitting/licensing and piloting green hydrogen projects and derivatives, and 3) reviewing the regulation of natural gas and its infrastructure to promote the introduction of hydrogen quotas.
- **Policies for social and local development** aiming to involve communities in decision-making and achieve transversal sustainable development by 1) using transparent participatory mechanisms between communities and projects, 2) reducing market barriers and exploring ways to leverage hydrogen production

into isolated electric systems, and 3) assessing challenges and opportunities of hydrogen related to their land and natural resources usage.

- **Policies to promote capacity building and innovation** by 1) identifying needed competencies and technical skills for the new industry in a joint effort by industry and academia, 2) building an R&D roadmap to develop further technological knowledge and capabilities to accelerate the green hydrogen deployment, and 3) fostering the adoption of green hydrogen in public companies.

Pilot Projects in Chile. Though some of Chile's specific hydrogen policies and incentives are still being drafted, the country has already seen a boom in green hydrogen pilot projects. These projects, which are in different stages of formation, span a variety of potential uses for hydrogen, including fuel cell vehicles, blending with natural gas, and use as an input for ammonia production. So far, the pilot projects in the south of the country are showing encouraging results, and have already produced synthetic diesel (e-diesel or carbon-neutral diesel) that can be easily used in existing automobiles, directly replacing traditional fuels (Hanley 2022).

Around 39% of the 28 the green hydrogen projects in Chile are explicitly solar photovoltaic (PV) projects. For this report, we focus only on solar PV projects. These projects, listed in Table 1 below, identify the most promising applications and strategies for developing the green hydrogen industry in Chile, and make the country an emerging incubator for green hydrogen innovation. In the future, these pilot projects may help Chile become not only a producer of green hydrogen, but also a hub — and exporter — of green hydrogen technical knowledge and expertise.

Table 1. Currently Announced Green Hydrogen Projects in the Antofagasta/Atacama Region

Name of Project	Company	Capacity of Electrolyzer	Final Use	Status	Start date	Projections (*)
Planta Piloto Movil	CICITEM	20 kW	Fuel Cell Test	Operational	2022	to be defined
Atacama Hydrogen HUB	Humboldt Hidrogeno Verde	2.000 MW	Ammonia	Pre-feasibility	2027	to be defined
Hydra	Mining3, Engie, Hexagon Purus	3 MW	CAEX Fuel Cell	Pre-feasibility	F2:2022 F3:2023/2024	F4: 2025/2026
Adelaida	Aes Andes	2.5 MW	H2 Fueling Station	Feasibility	2024	-
HYEX	Engie/Enaex	26 MW	Ammonia	Pre-feasibility	2025	F2: 2030

-	FCAB	3 MW	Train Fuel Cell	Building	2024	yes
-	GNA	1.5 MW	Truck Fuel Cell	Pre-feasibility	2025	undefined
-	Inv Farias	14 kW	Forklift	Feasibility	2023	yes
AMER	Air Liquide Chile	80 MW	Methanol	Feasibility	2025	undefined
-	AES Andes	-	Ammonia	-	2025	-

Notes: (*) F stands for phase, i.e., stage of project

Source: CICITEM.

Comparative Advantages of Chile for Hydrogen Production

Four key factors make Chile a competitive location for a green hydrogen industry.

Presence of Globally Competitive Solar Resources. Solar radiation is abundant in Chile's Antofagasta region, and in that region the Atacama Desert has one of the highest levels of solar radiation in the world (ESMAP, 2020a). Solar radiation in the region has load factors of 24% in single-axis monofacial photovoltaic panels (and around 35% in the case of single-axis tracking).[11] Also, the country's central region, solar energy is a more competitive source of electricity generation than fossil fuels.

Its solar power can be provided at cheap cost. Gallardo et al. (2021) estimate that in Antofagasta the levelized cost of energy (LCOE) from an on-site dedicated solar PV field was US$21/MWh in 2018 but would drop to US$18/MWh by 2025.[12] Likewise, the authors estimated that the LCOE for projects with power purchase agreements PPAs (with connection to the grid), which were approximately US$23/MWh in 2018, would decrease to US$18/MWh by 2025. By way of reference, the global weighted average LCOE for solar PV is US$48/MWh for solar PV with individual projects.[13]

Overall, the country could support approximately 1,800 GW of wind, solar, and hydro energy generation (Ministerio de Energía de Chile, 2020). Hydrogen can be used in the electricity sector to provide backup for intermittent renewables.

Accessible Water Resources. Chile is a thin coastal country with large coastline, which makes seawater accessible for the electrolysis process. Water management in hydrogen systems is critical to developing a sustainable hydrogen industry and to minimizing the industry's contribution to regional water stress and competition.

Since pure water is needed for electrolysis, water purification is required when seawater is used. Impure water — water with high conductivity, i.e., with high concentration of salts — produces corrosion in the electrodes damaging the electrolyzer. [14]

Water purification systems typically account for just 1%-2% of the total costs of large-scale electrolysis systems (Holst et. al., 2021). As long as the water purification is effective, electrolysis systems can use most water sources, providing flexibility to select a source based on factors such as cost-effectiveness or sustainability. Thus, the cost of water treatment can vary widely, as it depends on the water source, the transport distance and possible waste disposal.

Unlike tap water,[15] using seawater and wastewater require additional pretreatment processes — such as upstream desalination units — which add cost.[16] While useful in regions with scant fresh water supplies, seawater may also pose environmental risks (see Box 2). However, even the more costly water treatment processes are still only a small part of total electrolysis costs.

The total cost of $1m^3$ of desalinated water is US$1.00, and desalinated water amounts to between 1%-2% of operating costs for a green hydrogen plant (IRENA 2022b). In regions with lower-than-average electricity costs — such as northern Chile — the cost of desalination can be even less (IRENA 2022b). Moreover, desalination plants are already in place in Antofagasta to supply the water needs of communities and mining operations in the region.[17]

National Policy and Government Commitment To Incentivize a Hydrogen Economy. The Chilean government was one of the first governments to publish its roadmap and national strategy plan for hydrogen in 2020. Furthermore, the current government is confirming this commitment and is implementing the policies needed to incentivize the market. Some of the key policies in place are:

- Public funding availability for the development of hydrogen projects through entities such as the Chilean Production Development Corporation (CORFO). In December 2021, CORFO awarded a total of US$50 million, in the form of grants, to six renewable hydrogen production projects (IRA 2022). In November 2022, the government signed two agreements with multilateral banks, one with the World Bank Group for a total of US$350 millions and the other with InterAmerican Development Bank (US$400 million) to fund green hydrogen projects.[18]
  CORFO has been invited to be part of the new Hydrogen for Development Partnership (H4D) — a global initiative of the World Bank Group announced during COP27 — that aims to boost the deployment of low-carbon hydrogen in developing countries.
- A carbon pricing (taxing) policy has been implemented since 2017. Although the carbon tax is not high as in European countries --in Chile the tax has been levied at a rate of US$5/ton CO2 — the existence of the carbon tax signals to the market the national objective towards decarbonization. In addition, the institutions involved

may have already sufficient experience and information to better optimize this mechanism.

Robust Existing Infrastructural Networks, including pipelines, ports, and roads located near areas with high solar potential, which could support the transport and even export of green hydrogen. Current pipeline infrastructure — Atacama and Taltal pipeline — primarily build to transport gas, can be repurposed to transport syngas by blending natural gas with hydrogen (up to 20%) with minimal modifications (IEA 2022b). Newer infrastructure can be built once the market expands. The existing pipeline is also connected to the Mejillones seaport, opening the possibility of exports in the future. The Mejillones seaport is also connected to the railroad network and to the main road network.

Opportunities for Chile's Hydrogen Production

The global crisis that began with the COVID-19 pandemic, now affected also by the Russian-Ukrainian war, has reinforced the push to speed up the energy transition, to attain energy security and reach climate goals. With the significant growth in global interest on developing low-carbon hydrogen markets, resources to develop the technology needed to scale up hydrogen production have become more widely available. In line with this trend, we identify below several opportunities for Chile.

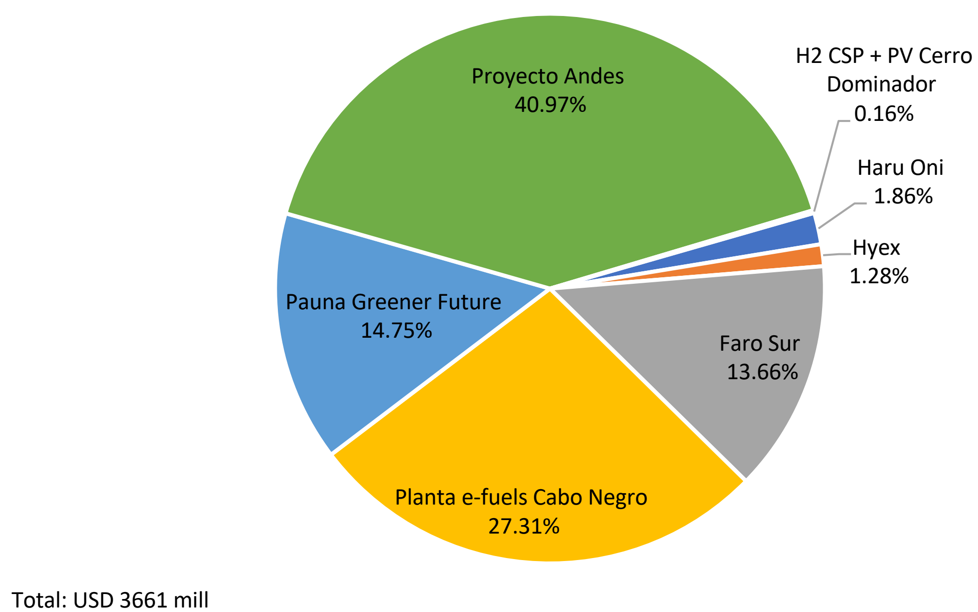
Wider Collaboration Across Institutions at the National and International Level. Recognizing both the economic and environmental potentials of green hydrogen, key representatives from private, public, and academic sectors have started collaborations with national and international green hydrogen associations. The Chilean hydrogen association (H2Chile) was created in 2018 to accelerate the energy transition, promoting hydrogen as an energy vector and its use in a variety of applications from industrial, commercial, residential to transport. More than 60 companies from the energy sector and related markets participate in this association, including energy companies such as Engie, Enel, Air Liquide, EDF renewables; engineering service companies such as ABB, Siemens energy, Finning CAT; mining companies such as Angloamerican, Antofagasta Minerals, and Codelco; and also shipping transport companies such as GEN (*grupo de empresas navieras*).[19]

H2Chile is also a strategic ally of a broader regional collaboration platform: the Hydrogen Congress for Latin America and the Caribbean (H2LAC).[20] H2LAC was found in 2020 by key international partners include EuroClima+ from Europe Union, ECLAC, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), and the World Bank. Participants from the public sector include the ministries of energy of Chile, Colombia, Argentina, Uruguay, and Bolivia, among others.

Additionally, there are sectoral public-private initiatives such as the Corporacion Alta Ley that emerged from the National Mining Program of Alta Ley — it coordinates public, private, and academic efforts to promote innovation (R&D), productivity and competitiveness toward sustainable development in the mining industry. Created in 2015 by CORFO as part of its "Strategic program of smart specialization" (Programa Estratégico de Especialización Inteligente de CORFO). Corporación Alta Ley launched its technological roadmap for the mining industry in 2019; it includes the use of green hydrogen in the industry. The Alta Ley organization also has allied institutions in Peru, Brazil and Ecuador, and recently published, in conjunction with SAMMI in Peru, the first binational roadmap for the implementation of green hydrogen in the mining sector in Peru and Chile.[21]

Private Companies in Chile are Also Willing to Commit and Invest in Green Hydrogen. As of August 2022, the Chilean electric generation industry had committed to investing US$23 billion in renewable energy over the following five years, 15.5% — around US$3.6 billion — of which will dedicated to green hydrogen projects — 44% is allocated to solar power and 30% to wind (Ministerio de Energía de Chile 2022b). Figure 11 shows the share of investment commitments by project.

Figure 11. Chile: Investment Commitment in Green Hydrogen Projects, Share by Project (2022)



Source: Ministry of Energy of Chile.

Greater Financing for Hydrogen Worldwide Can Boost Market Development and Accelerate Hydrogen Technology. Substantial investment in hydrogen can accelerate the technological advances required; developing improved electrolyzers, distribution and transportation systems. Therefore, it can lead to faster market development, by diversifying and scaling up demand. Even if financing is not available to all projects, these investments will certainly have spillover effects in favor of the global market, by improving technology and reducing costs.

Financing by Multilateral Organizations. Multilateral organizations have also made funding initiatives available for green hydrogen projects in Latin America via climate and clean energy funds. Several of these initiatives are described below:

- The Climate Investment Fund (CIF), comprised of the Clean Technology Fund and the Strategy Climate Fund, is an $8 billion multilateral climate finance partnership that channels project financing through the World Bank Group, the International Finance Corporation, and four development banks (Inter-American Development Bank IDB, African Development Bank, Asian Development Bank and the European Development Bank). In Latin America to date, CIF has 117 approved projects — in Brazil, Colombia, Argentina, Peru, Ecuador, Paraguay, Bolivia, Mexico among others — involving $1.3 billion in funding and $11.6 billion in co-financing. A significant share, 60%, of those funds is directed to projects under the scope of the Clean Technology Fund, which includes green hydrogen.
- In July 2022, the IDB and Green Climate Fund announced the co-creation of the E-mobility Program for Sustainable Cities in Latin America and the Caribbean. This program will provide $450 million in concessional loans and grants to nine Latin American countries to develop hydrogen projects related to transportation (IDB 2022). Additionally, the IDB has been working on supporting policies to strengthen adequate regulations for new technologies. For example, it approved a $300 million policy loan for Chile, to help the country's energy transition process, to develop regulation and development of green hydrogen (Madrigal Martinez 2022).
- Hydrogen for Development Partnership (H4D) is a global initiative of the World Bank Group announced during COP27[22] that aims to boost the deployment of low-carbon hydrogen in developing countries.
- Scaling Climate Action by Lowering Emissions (SCALE), a multi-donor program comprised of states, the private sector, and foundations that is supported by the World Bank, will pool funding for impactful projects to reduce greenhouse gas emissions. Its initial funding target is $1 billion by the end of 2023, and it expects to increase this investment to $5 billion in the medium-term

Public Financing. The largest sovereign investors in hydrogen are Japan, the European Union, Germany, and the United States of America.

- **Japan.** By early 2022, the Japanese government had invested $670 million to develop the hydrogen and fuel cell business as part of its national strategy to become the world's first hydrogen society (IRENA 2022b). Fuel cell technology is still in the early stages of market development.
- **European Union.** The European Union has allocated $4.56 billion in annual funding for hydrogen projects for the period 2021-2030. In November 2021, the EU Commission joined the Clean Hydrogen Partnership, a public-private collaboration to support research and innovation in hydrogen technology, with an initial investment of $1 billion for the 2021-2027 period and a subsequent investment of $211 million in May 2022, as part of its REPowerEU Plan (IEA 2022b).
- **Germany.** During the 2022 COP27 meeting, Germany announced that its KfW Development Bank would invest $572 million to speed the development of a global green hydrogen economy and fast-track the energy transition, a contribution that they plan to increase to $2.5 billion overtime (Steffen and Braun 2022).
- **United States.** The U.S. has also committed $9.5 billion over a period of five years for the development of clean hydrogen technology — that includes green hydrogen technology among others — and hydrogen hub demonstration projects through its Infrastructure Investment and Jobs Act. In its Hydrogen EarthShot program, the U.S. has also set a "1-1-1 goal" to reduce the cost of clean hydrogen to $1 per 1 kilogram in 1 decade (IRENA 2022b). The Inflation Reduction Act created additional support through a tax credit of up to $3/kg for production of qualified clean hydrogen[23] (with lowest associated emissions) for a 10-year period. Although rules and procedures are still being defined, these funds may indirectly help other nations by lowering the cost of green and other clean hydrogen technology and making investment in hydrogen projects more appealing and by stimulating demand for clean hydrogen.

Private Financing. The private sector offers a third source of funding. Just recently, the Bezos Earth Fund, the Rockefeller Foundation and the U.S. State Department announced the Energy Transition Accelerator (ETA), which could help to catalyze private capital for clean energy transition in emerging and developing countries.[24]

Global Interest in Scaling Up the Electrolyzer Market. A number of countries have implemented policies to encourage electrolyzer manufacturing that should reduce costs as production scales up and subsidies come into effect. By 2022, 25 countries (almost double the 2020 count) and the European Union had created national hydrogen strategies that set targets for expansion of electrolysis technologies (IEA 2022b). The European Union, for example, aimed to install at least 6 GW of electrolysis capacity between 2020 and 2024, and expand such electrolysis capacity to 40 GW before 2030, according to its Hydrogen Strategy in 2020. Chile aims to install 5 GW of electrolyzer capacity by the end of 2025.

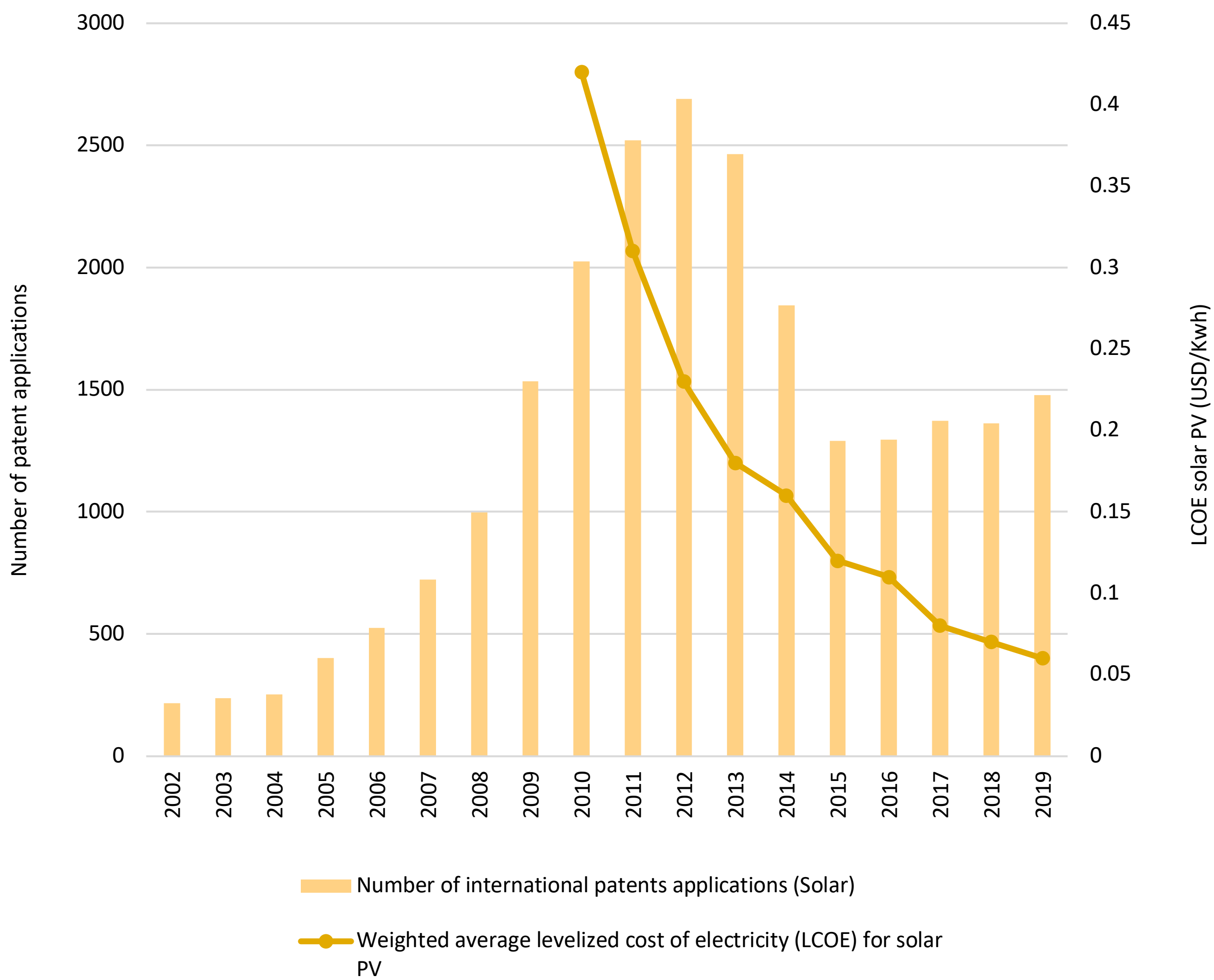
To achieve these goals, the production capacities for electrolyzers must be expanded significantly. These targets will require a significant expansion of global electrolysis capacity, which in 2021 was approximately 500MW (up from 300MW registered in 2020) (IEA 2022a).

But efforts are being made. In May 2022, with a Joint Declaration signed between the EU Commission and 20 electrolyzer manufacturers, the industry agreed to reach a combined annual electrolyzer capacity of 17.5 GW by 2025 and to keep increasing capacity according to the demand by 2030 (European Commission 2022).

Expected Cost Reduction of Electrolyzers. Currently all existing electrolyzer types are more expensive than traditional, carbon-intensive methods for producing hydrogen. However, some factors indicate that electrolyzer costs will likely decrease in the coming years:

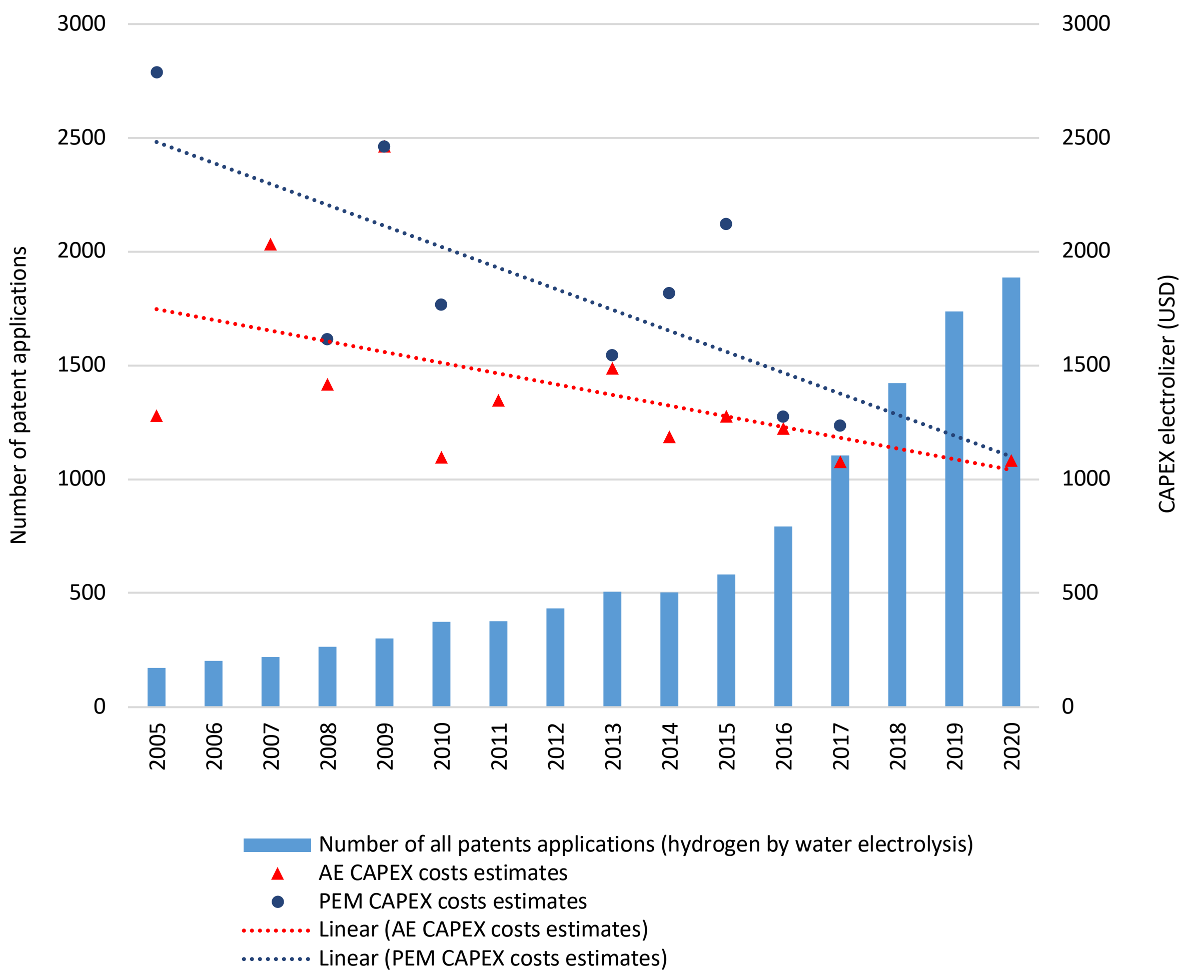
- **Incentives for Improving Electrolyzers.** Incentive packages such as the recently passed US's Inflation Reduction Act of 2022 (IRA) are likely to help lower the costs of electrolyzers. The IRA provides a US$3/kg subsidy for hydrogen produced with minimum CO2, and also earmarks funding for developing technology and applications for green hydrogen. The IRA and other policies will likely increase the demand for electrolyzers, potentially contributing to economies of scale and manufacturing efficiencies that will help reduce their price.
- **Competition and Innovation.** While rising demand will likely encourage manufacturers to compete and reduce costs, ongoing innovations (Figures 12 and 13) — as evidenced by a growing number of electrolyzer patents — may also help improve efficiency and reduce materials costs. Companies including Siemens Energy, Plug Power, Toshiba, Air Liquide, McPhy Energy, ITM Power, Idroenergy, and Next Hydrogen are developing or improving upon electrolyzer technologies (Deza 2022). In fact, two European manufacturers have already announced that considerable cost reductions are anticipated by 2025.[25]

Figure 12. Evolution of Patents and Cost of Solar PV Energy (2002-2019)



Sources: EPO and IRENA 2022; Glenk and Reichelstein 2019; IRENA 2022a; Nurton 2020.

Figure 13. Evolution of Patents and CAPEX Cost of Electrolyzers (2005-2020)



Note: The capital expenditure (CAPEX) shown is based on Glenk and Reichelstein 2019. For certain years, the costs listed above correspond to the average of the values from various sources presented by Glenk and Reichelstein 2019.
Sources: EPO and IRENA 2022; Glenk and Reichelstein 2019; IRENA 2022a; Nurton 2020.

Existing Domestic Hydrogen Demand Is Mostly Near Renewable Energy Sources. This happens particularly in the north of Chile with the mining industry, as well as with the metropolitan energy consumption — as a transport fuel and for industrial activities — in the country's central zone. Given the existing network infrastructure between regions, the transmission grid is mostly integrated.

- **Mining Is a Key Player for Market Development.** In Chile, mining is the largest energy consumer. Mining accounts for 33% of electricity and 20% of diesel consumption (Kracht and Salinas 2021).[26] Copper mining alone generated 19.6 million tons of CO_2 in 2015; 18% of total national emissions (Kracht and Salinas

2021). The diesel consumed by mining haul trucks, about 3,000 liters per day per truck, accounts for half of the mining industry's total energy use (Vaccarezza 2022).[27] Replacing just 20% of the copper mining fleet in Chile with hydrogen-fueled trucks would avoid an estimated 1.4 million tons of CO2 emissions by 2030 (IEA 2021b).

- **The Transmission Grids of the North and Central Regions Are Integrated.** To overcome one of the major difficulties for renewable energy expansion in the north of country (where the Atacama Desert is) in November 2017, the transmission grid from the north region (*Sistema Interconectado Norte Grande* SING) and the grid from the central region which includes Santiago, the capital city (*Sistema Interconnectado Central* SIC) were interconnected. This was made possible first by the installation of a new interconnection line between Atacama and Antofagasta in 2017, and then a line between Atacama and Santiago in June 2019 (see Figure 14 in the Appendix), which has allowed for electricity price reductions in the south and price convergence between regions (Gonzales et. al 2022).

Chilean Openness to Trade May Facilitate Exporting Hydrogen to Asia and Europe. Chile's multiple free trade agreements have led to development of international collaborations; such partnerships offer one promising way to finance domestic green hydrogen projects.[28] Between 2020 and 2022, Chile developed cooperation agreements on hydrogen development with Germany, South Korea, France, Netherlands, the United Kingdom, and Singapore, and had already established specific hydrogen memorandum of trade agreements with Germany, the Netherlands, and South Korea (IEA 2022b). Table 2 summarizes some of the existing memorandums of understanding (MOU). It is worth noting that MOUs are the first step to contracting, and although they may not result in actual projects, they give market signals and may influence expectations.

Table 2. Chile's Signed Agreements and Memorandums of Understanding (MOU) for Green Hydrogen Production

Type of agreement	Signatory party	Objective	Year
Cooperation agreement	Germany	Signed with the German Ministry of Economics and Energy to strength the cooperation related to green hydrogen development. It also created a workgroup to identify viable green hydrogen projects.	2022
MOU	Germany	Signed with the German Ministry of Economics and Innovation of the State city of Hamburg and Port Authority to join efforts create the conditions for the early export of hydrogen and hydrogen derivatives to Hamburg and Central Europe, and to promote the rapid development of a self-sufficient hydrogen market in both countries.	2022

MOU	Netherlands	Signed with the Port of Rotterdam to establish collaboration mechanisms that help to ensure a supply chain of green hydrogen produced in Chile and distributed all over Europe.	2021
MOU	Belgium	Signed with the ports of Antwerp and Zeebrugge to facilitate green hydrogen flows between continents.	2021

Source: Chilean Ministry of Energy.

Potential Importers of Hydrogen May Include Mobility Uses. For example, Japan and South Korea have both published ambitious plans to transition to a hydrogen-based energy economy. Japan has already made significant capital investment in infrastructure and in 2022 had over 160 hydrogen refueling stations and over 6,700 fuel cell vehicles (FCVs), as well as approximately 400,000 combined heat and power (CHP) fuel cells in residential buildings (Gallardo et al. 2021; Samsun et al. 2022; Simader and Vidovic 2022).[29] South Korea, meanwhile, has the largest fleet of FCVs on the road, over 19,000 as of late 2021 (Samsun et al. 2022). European countries are also potential green hydrogen importers. In 2022, for instance, Germany signed memorandums of understanding with Canada and Chile to purchase green hydrogen, and with Egypt and India to collaborate around green hydrogen production.

Antofagasta as a Hydrogen Hub

Given its location, cheap renewable power sources, access to seawater, existing port, pipeline and transmission grid infrastructure, and proximity to existing mining activities and ammonia industry, Antofagasta is a suitable site for a hydrogen hub[30] and even a hydrogen corridor — such a corridor connects many nearby individual locations where synergies allow for reduced service coordination and distribution costs, with more efficient access to network infrastructure (Altman et. al., 2022). By establishing suitable planning mechanisms and tariff structures defined by reliable regulators, governments can encourage potential producers, transporters, and buyers to jointly develop critical facilities which have open access to third parties.

Green hydrogen derivatives, like green methanol,[31] could be used to replace diesel for heavy-duty transportation used in mining activities, helping to reduce the carbon footprint of Chile's copper industry and decarbonize mining. This is particularly relevant as Chile has reserves of two minerals crucial to the energy transition: copper and lithium, for which demands are expected to significantly increase. Moreover, mining represents between 57% to 65% of the economic activity of the Antofagasta Region, which also produces over 45% of the national mining GDP.[32]

Developing a green hydrogen industry and decarbonizing its copper industry could help cement Chile's reputation as a hub of the energy transition and sustainable economy, while reducing diesel inputs. Further, green ammonia would substitute gray ammonia in the fertilizer and explosives industries.

Regulatory Framework

The hydrogen industry, if properly regulated and incentivized, can foster regional growth and employment opportunities, and also encourage innovation through pilot projects to identify best practices and fine-tune emerging technologies.

The role of government is to provide rules and standards to guide the planning, final investment decision, construction, and operation phases of hydrogen plants. However, because an international hydrogen market is still in its initial, conceptual phase, there are no unified international standards.

The Chilean Ministry of Energy has designed a calendar with three phases to adapt existing regulations and design new ones to facilitate the development of this new energy vector (Eterovic 2022):

First Phase 2020-2023 to elaborate general rules for hydrogen installations, quality specifications and delivery (multifuel service stations).

Second Phase 2024-2027 to prepare the rules for hydrogen transport by pipeline network, for its use for electric power generation, technical and safety requirements for light and heavy transportation in coordination with the Ministries of Transportation and Mining.

Third Phase 2028 forward to prepare regulations for handling hydrogen in port facilities for export in conjunction with the Ministries of Transportation and Defense.

Currently, Chile does not have a comprehensive hydrogen regulatory framework. However, it is developing new laws and modifying existing legislation to meet the needs of this new industry, as summarized below.

Law 21.305 — Law of Energy Efficiency, enacted in February 2021. This new law includes hydrogen as energy vector — thereby broadening its definition as a fuel, and not only as a dangerous substance. It designates the Ministry of Energy as responsible for the national plan for energy efficiency that must be updated every five years.

The updated definition to hydrogen as a fuel is very relevant and allows for more accurate regulation design, which is consistent to regulations in Europe where the focus is on regulating hydrogen as a fuel. This is a major improvement since when hydrogen was treated as a dangerous substance, it was subject to different regulatory agencies depending on its use (see Table 8 the Appendix) such as the Ministry of Health, Ministry of Transportation and Telecommunications, the International Maritime Dangerous Goods

(IMDG) Code, the Ministry of Mining, and Ministry of Labor and Social Security (Centro Energia UC 2020; Eterovic 2022). Another key improvement made by this law is that it appointed the Ministry of Energy and the Superintendency of Electricity and Fuels (SEC) as the main authorities to oversee and coordinate hydrogen regulation.

The law also requires large energy consumers to apply energy management systems and to report their consumption to the SEC. According to the latest exempt resolution RE 13 published early March 2023, there are around 150 companies identified and listed as consumers with energy management capacity (*consumidores con capacidad de gestion de energia*, CCGE) which together account for more than one third of the national energy consumption. These companies are obligated to implement energy management systems that cover at least 80% of their total energy consumption and must implement measuring and verifying systems as well.[33]

Law 21.505 — Law that Promotes Electrical Energy Storage and Electromobility, enacted in November 2022 by the Ministry of Energy. This Law modifies the previous General law of electrical services (Law 4) by including the storage systems within the generation market. This would allow the expansion of non-conventional renewable resources within the electricity matrix through the usage of storage technology such as hydrogen. The law also establishes incentives for the adoption of electric vehicles and promotes their participation in the electricity market.

Law 19.300 — Environmental Framework Law, enacted in 1994, and later reformed by Law 20.417 in 2010. This law created the Ministry of Environment, the Service of Environmental Evaluation (SEA) and the Superintendency of Environment (SAM). While the Ministry proposes environmental regulations, the SEA ensures environmental compliance, managing the Environmental Impact Assessment System (SEIA), also fostering and facilitating community participation and Indigenous consultation. On the other hand, SAM is responsible for supervision and imposing sanctions for violations to environmental rules, such as quality standards and/or prevention plans of environmental decontamination.

Decree Law 1.939 — Rules for Acquisition, Administration, and Disposal of State-owned Assets, enacted in 1977, and reformed several times, most recently in 2019. These rules are applied, administered, and monitored by the Ministry of National Assets (MBN), which administers and allocates these state-owned assets via leases, sales, grants, concessions, including rights of way, etc. The Ministry works at the regional level through its Regional Ministerial Secretariats (SEREMIS). In Antofagasta, the authority representing the Ministry is the Regional Secretariat of Antofagasta.

Exempt Resolution RE 1302, 2022 — National Plan for the Promotion of Green Hydrogen Production Fiscal Territory, this resolution published in December of 2022 modifies and complements previous resolution RE 998 of 2021. In collaboration with the Ministry of Energy, the Ministry of National Assets published a plan to speed up the licensing process for green hydrogen projects and derivatives.[34] The plan establishes a single-contact point (or window) for direct applications to obtain onerous concessions of fiscal lands for energy generation and production of green hydrogen and derivatives. Likewise, it determines the concessional rents and the accepted guarantees of execution and rent payments.

In addition to defining the technical requirements, how fiscal land is allocated, and other application and project requirements, this plan sets a schedule for the application procedure of direct onerous concessions, setting the final step date — the date for contract approval (see Table 9 in the Appendix).

The concession applicants are subject to three project development stages: 1) studies and environmental evaluation stage,[35] (2) construction stage,[36] and 3) operation stage.[37]

Law 21.435 — Law that Reforms the Water Code, enacted in 2022 by the Ministry of Public Works, which oversees compliance through the General Directorate of Water. This institution manages the hydro sources in the country, and oversees the usage of terrestrial waters, safeguarding its preservation and availability for a sustainable socioeconomic development. Note that the code applies to terrestrial water and not to seawater: Surface water and groundwater are considered terrestrial, while sea water is maritime. If water is considered terrestrial, then water rights can be treated as a private good and there is a market for that. It is not yet clear whether desalinated water is considered terrestrial or maritime, but one can argue that given the industrial process the outcome can be treated as terrestrial water.

Law 20.500 — Associations and Community Participation in Public Management, enacted in 2011. Additionally, in 2018 the Ministry of Energy published its “General norms for community participations” (RE 117, 2018), by which it established the formal and specific modalities of participation in the energy sector, and participation mechanisms such as public consultations, participatory public accounts, information access, and the civil society council. The ministry also created the Division of Community Participation and Relations and presented the Guidelines for Participation Standards for the Development of Energy Projects. The aim is to strengthen awareness and involvement of communities with energy education and capacity building (see Box 1 below about social acceptance in hydrogen projects).

Regulations Being Prepared. Among the regulations that are being drafted are revisions dealing with gas and its infrastructure to allow for green hydrogen blending quotas (between 10% to 20%) in the gas pipelines. In addition, new pipeline installations would be expected to be able to handle at least 20% of hydrogen in the gas mix (Eterovic 2022). This measure is expected to foster demand for hydrogen by allowing the use of pipeline infrastructure and preparing for its larger network usage by guaranteeing adequate pipeline infrastructure and minimum safety standards in its distribution.

Existing Guidelines to Support the Transition to a Comprehensive Regulatory Framework. As mentioned before, by the end of 2022, there were around 28 green hydrogen projects. Hydrogen projects need to have feasibility studies, and compliance with safety standards to get permits and licenses. Since safety standards and accreditation for hydrogen installations are still not well established, Chilean authorities — the SEC, the National Service of Geology and Mining (SERNAGEOMIN), and the Service of Environmental Evaluation (SEA) — have provided guidelines for hydrogen projects to facilitate the permission process. Current guidelines in place are the following:

- SEC's "Guidelines for Authorization Application for Special Hydrogen Projects" (*Guía de apoyo para solicitud de autorización de proyectos especiales de hidrógeno*): This guideline, published in May 2021, aims to assist interested parties to make applications and implement hydrogen projects that involve production, transport, distribution, storage, or consumption of hydrogen as a fuel. It allows the use of international safety standards from institutions such as NFPA, European Standards EN, ASME, ISO, SAE International, CSA, IEC, EIGA, and ANSI (Ministerio de Energia and SEC 2021).
- SERNAGEOMIN's "Guide for Implementation of Pilots and Validation of Technologies that use Hydrogen as Fuel in Mining" (*Guía de implementación de pilotos y validación de tecnologías que utilizan hidrógeno como combustible en minería*): Published in October 2021, this guideline defines the requirements for implementation of pilot projects that involve handling or using hydrogen as a fuel in mining operations. It also tries to standardize the evaluation criteria and it also allows the use of international standards.
- SEA's Guideline "Evaluation Criteria of the System of Environmental Impact Evaluation: Introduction to Green Hydrogen Projects" (*Criterio de evaluación en el SEIA: Introducción a proyectos de hidrógeno verde*): Published in January 2022, this guideline presents the background requirements that hydrogen project proposals (for production and storage) need to be assessed by the System of Environmental Impact Evaluation (SEIA). Although there is no specific category for hydrogen production, storage and transport, impact evaluation assessments are required for green hydrogen projects whenever part or all of the project can be framed within at least one of the categories defined by the rules of the SEIA and the Environmental Framework Law (Law 19.300) — for example, projects that involve water use, energy generation plants greater than 3 MW, high voltage transmission lines, or production of toxic substances, would be included. More generally, impact evaluation is needed for any project that poses an environmental risk to the community, is located near protected areas, or implies alterations to cultural or ecological places (articles 5-10 of the rules of SEIA).

Although these guidelines are a temporary instrument for use in the absence of a comprehensive regulatory framework, it is not clear whether they are mandatory rules or just support guidelines to ease the application procedure. There are still many institutions involved and many permits to obtain, so the process can be unnecessary lengthy for pilot projects.

Box 1: Social Acceptance

Most of the studies on social acceptance have focused primarily on consumer-oriented hydrogen applications such as fuel cells and hydrogen fueling stations for private cars, as well as residential heating and cooking (Ricci, Bellaby, and Flynn 2008; Sherry-Brennan, Devine-Wright, and Devine-Wright 2010; Emodi et al. 2021, Achterberg et al. 2010; Emodi et al. 2021; Lozano et al. 2022).[38]

Some actionable best practices derived from the literature include:

- Engage local stakeholders early in the process (Stalker et al. 2022).
- Create opportunities for participatory planning to ensure that projects maximize local benefits and minimize local costs (Achterberg et al. 2010; Sherry-Brennan, Devine-Wright, and Devine-Wright 2010; Emodi et al. 2021).
- Avoid "fuel-neutral" projects that generate hydrogen from both renewable and non-renewable sources (Dumbrell et al. 2022).
- Provide accurate, nuanced information about possible risks, costs, and benefits (Lozano et al. 2022).

Local demonstration projects can also increase support because they allow stakeholders to see the tangible footprint and potential benefits of hydrogen projects (Sherry-Brennan, Devine-Wright, and Devine-Wright 2010; Emodi et al. 2021).

The cost and accessibility of hydrogen fuel for locals also impacts community support (Dumbrell et al. 2022); likewise, projects beneficial to local energy affordability and reliability may outweight export-driven projects in terms of community support.[39]

In the context of South America, two unique characteristics of the region that may change the parameters and challenges of social acceptance are:

1. Levels of trust in government and industry are often lower than in Europe (Keefer and Scartascini 2022).
2. Most hydrogen infrastructure will likely be for production, use in hard-to-decarbonize industries, and export, if feasible in the long term.

Green hydrogen production, unlike consumption, also requires large wind or solar projects, which have begun to generate resistance worldwide (Temper et al. 2020), including countries such as Colombia (Ullman and Kittner 2022), Mexico (Mejía-Montero, Alonso-Serna, and Altamirano-Allende 2020), and Chile (Vallejos-Romero et al. 2020). The possibility that communities in isolated areas not served by the power grid may benefit from having access to renewable electricity is not often highlighted.

Potential Challenges to Hydrogen Market Development in Chile

Developing and Scaling the Technology and Consumer Base for Hydrogen Use

Expanding support for research and development activities is crucial to accelerating technological advances and cost reduction. Advances in technology and infrastructure will, in turn, create opportunities for new uses. Incentivizing existing consumers of gray hydrogen and ammonia to switch to green hydrogen and its chemical derivatives can create demand, and pilot projects can help identify the technologies with the greatest potential to achieve economies of scale. Future developments in fuel cell technology and hydrogen long distance transportation will determine whether international trade becomes feasible and competitive.

Regulatory Challenges

Successful market development for hydrogen will depend on many factors: level of investment on hydrogen technology and production, infrastructure readiness, local and international demand, and overall market rules. Governments can incentivize local market developments with clear, transparent, and non-restrictive competitive regulations, by promoting private sector participation and market competition. International cooperation, on the other hand, will allow for global market development through harmonized standards.

Therefore, it is crucial to implement a competitive regulatory framework that fosters investment and infrastructure development while gaining acceptance of local communities and other stakeholders, green hydrogen as fuel relevant stakeholders. The regulatory framework needs to cover sectoral economic regulation — which includes access to resources, safety, and market incentives — and environmental regulations.

<u>Sectoral Economic Regulations</u>

Access Regulation

Access to Resources. Securing a transparent and competitive access to inputs can reinforce efficient allocation to most productive players. Green hydrogen projects require access to input resources such as land for solar PV power plants and access to water current or coastline access for their desalination plants to be able to perform their electrolysis. Regulation can be made clearer and streamlined for hydrogen projects.

- **Energy Supply Access.** A regulatory framework must establish a set of processes by which hydrogen plants secure the supply of renewable energy. These processes are likely to be different depending on whether a project is on or off the grid, but in either case a competitive bid approach could be considered for securing a solar plant connection, or a PPA or multiple PPAs. If an auction process is used, all bids by qualified parties should be evaluated in a fair and transparent manner.
- **Rules for Land Access.** Regulation of land access differs depending on the type of ownership. For state-owned land, it is crucial to create regulations to allocate land via a transparent, fair process such as an auction. Access to privately-owned land will

likely be negotiated on a case-by-case basis. Hydrogen projects will not only need land for their production plants, but also will need rights of way for transportation. In this regard, the recent national plan for promotion of green hydrogen production in fiscal land is a great tool to streamline the application of onerous concessions to land.

- **Rules for Water Access.** Water access regulations for hydrogen projects must account for both the source (fresh, gray, or seawater) and the purification process. Where fresh water is used, standards should consider how to balance hydrogen plant needs with competing uses such as those of agriculture, wetlands, or municipal consumption (Fan et al. 2022). Where seawater is used, the impacts of desalination should be studied, regulated, and monitored (see Box 2).

Since many of the green hydrogen projects in the Antofagasta region consider using desalinated water, it is important to have a clear and unified regulation that covers all aspects of seawater usage for desalinization: licenses and permits, construction, installation, distribution, residual disposal, etc. On the other hand, there is not a standardized criteria for desalinization projects in the Environmental Impact Assessment System (Tapia 2022). By the end of 2022, such structured and unique regulation does not exist in Chile. For example, currently, as maritime goods, seawater is considered as a public good. To get access to the coastline, extract and transport the water, an authorization from the Sub-secretariat of the Army Forces of the Ministry of National Defense is required (Saa 2022). If transported inland, it requires rights of way, therefore it may be subject to further authorizations. In case the water passes through the land of indigenous communities, it requires authorization from these communities, and if it is treated as terrestrial water, it needs to be regulated by the Code of Water.

Open Access Rules. This refers to regulation to guarantee all involved companies have access to the infrastructure, especially to essential facilities, promoting competition and reducing inefficiencies of unnecessary infrastructure duplication. To avoid a costly and environmentally intensive build-out of infrastructure — such as ports and pipelines — for each hydrogen project (a challenge that the mining industry has faced), it is crucial that infrastructure is designed to be shared across multiple projects. Rules of open access need to be in place.

Safety

Hydrogen is highly flammable and needs to be carefully handled; its storage and transportation requires compression.

- **Safety Standards.** Standards are required to build and operate hydrogen plants, as well as to deliver hydrogen and its derivatives to the end user. Monitoring and enforcement of these standards are critical to ensure the safety of operations, employees, and surrounding communities, as well as end users. High-quality standards can also help build confidence in the environmental sustainability of green hydrogen, increasing its market value.

- **Pipeline Retrofits and Construction.** Standards for upgrading existing pipelines need to be followed as well as for building new ones, including establishing rights of way and open access rules. Also, the parties responsible for financing, building, and maintaining the roads that new projects will require must be determined.

The standards regulation for plants needs to be consistent including the power supply, the water supply, electrolyzer operations and storage of hydrogen, avoiding excessive and restrictive regulation.

Market Incentives

Fiscal incentives. According to Eterovic (2022), while there are no specific regulations to incentivize commercialization of green hydrogen in Chile, there are general rules that may benefit its development. For example, the new energy efficiency legislation includes an accelerated depreciation of three years for zero-emissions vehicles (electric, hybrid or FCV), which translates to important fiscal incentives for users of such vehicles. There are also fiscal incentives for private investment R&D established by Law 20.241. There are also fiscal benefits for extreme zones, which need to be reinforced. Notably, there are still not fiscal benefits for the Antofagasta Region, which is worrisome as it is a target region for solar PV hydrogen projects (Eterovic 2022).

Certification is important to guarantee quality and safety levels of the product, while reducing asymmetric information problems for end-users. Chile needs a certification system that sets secure technical standards of locally produced hydrogen, and allows end-consumers to distinguish green hydrogen from other production methods. International harmonized standards and an international certification of zero-emissions and sustainable hydrogen would be helpful but do not exist yet. This is also consistent with the lack of international standards to measure emissions (Angel and Marquez, 2022). Implementing a system of certification of origin for Chilean green hydrogen is recommended (Angel and Marquez 2022, Franco et al. 2022).

Carbon Pricing may help to provide right incentives to push consumers and producers toward a decarbonized economy. Chile already has a carbon pricing policy in place; however, its level is still too low to reduce the demand for fossil fuel products. The Minister of Environment has declared that the government is working on increasing the current carbon tax from US$5 to US$35/CO2 (Eterovic 2022). Doing so may help to boost demand, since increased demand for cleaner energy will reduce costs and make it relatively more competitive.

Reduce Entry Barriers. To encourage competition in this new market, entry barriers must be reduced by simplifying regulations and reducing administrative procedures. An appropriate regulatory market design is crucial to reach the scale required for a liquid hydrogen market (Medlock and Hung, 2023). Regulations must also incentivize investment and infrastructural development. Table 3 summarizes a list of factors and agents that might be involved in the development of the required infrastructure.

Table 3. Factors to Consider When Assessing a Project and its Access to Local Infrastructure

	Key factor(s) for private sector to evaluate	Government Institutions involved
Land access	Land property (is it public or private?) Location where the electrolyzer and the facilities associated to it be installed. Expansion of required land. Scope and variety of required services.	Energy, environmental and land Regulators Congress, Ministries of Energy, Environment and Culture, local governments.
Renewable energy	Is it built for the exclusive use of the electrolyzer or will the hydrogen plant be connected to the electric grid?	Energy regulator, Ministry of Energy
Water access	Does it have its own source, or does it need treated/desalinated water? If desalinated water is to be used, who will provide it with the required specifications? Is this available for multiple users? Infrastructure for water delivery to a plant.	Energy, environmental and land Regulators Congress, Ministries of Energy, Environment and Culture, local governments.
Access to market	Type of product delivered: Hydrogen: gaseous or liquid Chemical Feedstock: Petrochemical, Green Ammonia, Methanol, Alkalines/Oleofins Heat source Exports Harmonization of international standards to certify clean hydrogen.	Energy, environmental and land Regulators Congress, Ministries of Energy, Environment, and Culture, local governments, and port regulators. National and international standardization agencies.
Port Facilities	Distance to port facilities Type of facilities (suitable to handle hydrogen and chemicals)? International port requirements.	Energy, environmental and Maritime Transport Regulators, Congress, Ministries of Energy, Environment, Culture, and Transport, and local governments.
Pipelines network	Are there existing pipeline networks to and from a port that could be used to transport hydrogen? What size and how extensive are they? Do new networks need to be planned and built? Financing for upgrading/retrofitting or built the required infrastructure.	Energy, environmental, Transport and Infrastructure Regulators Congress, Ministries of Energy, Environment, Culture, Infrastructure, and Transport, and local governments. Financing agencies.

Source: Derived from authors' analysis.

Environmental Regulation: Environmental Impact Assessment

Hydrogen project applications must include an environmental impact assessment (EIA) that includes preservation measures, water supply, and the potential socioenvironmental and energy benefits and impacts to local communities. EIAs should also include a mitigation plan to address potential hazards, as well as addressing other concerns of the surrounding communities such as those regarding ancestral cultural heritage. The EIA should also consider potential externalities related to water use (including the energy requirements and environmental impacts of desalination), land use, and the construction of port, storage, and transport infrastructure. Finally, EIAs should assess and mitigate risks related to potential hydrogen leaks; even leaks that do not pose a security hazard may contribute to climate change (Fan et al. 2022; Ocko and Hamburg 2022).

Although there is legislation in place, there is no unified definition of hydrogen and its uses, which may hinder the administrative process for impact evaluation.

Box 2: Desalination and Environmental Impact

Desalination, which has been used for decades in arid areas to obtain potable water, has several established environmental impacts, including:

1) absorption of marine microorganisms and plankton;
2) the high salinity and residual chemicals contained in brine (waste from the desalination process);
3) the high energy consumption of desalination; and
4) air pollution due to emissions of greenhouse gases (GHG) and air pollutants.

When discharged into the sea (the most common practice), brine has a direct impact on marine ecosystems because it increases water salinity and may also increase its temperature. When disposed on land, brine can seep into and contaminate groundwater. Studies to model the spread and behavior of discharged brine, as well as mitigation measures such as large-scale brine dilution prior to discharge, can help mitigate these impacts. GHG emissions can be mitigated by using renewable energy sources rather than fossil fuels for desalination process.

Source: Panagopoulos and Haralambous 2020; Baeza, Vivanco and Harris 2022.

Community Engagement Challenges

Initiatives to develop green hydrogen hubs must pay heed to the concerns, opinions, and needs of local communities and the broader national public. Successful implementation and continuous operation of hydrogen projects requires community support to prevent or minimize social distress that may hinder future operations. Moreover, working with communities to limit socio-environmental and economic impacts and maximize benefits of green hydrogen projects is a key part of meeting the standards of climate and energy justice (Jenkins et al. 2016; Robinson and Shine 2018; Wang and Lo 2021).

Support for hydrogen projects increases with knowledge about hydrogen technologies, concern about climate change and other environmental issues, and trust both in government (to manage risks and maximize benefits of emerging industries) and in technology's capacity to address socioenvironmental problems (Achterberg et al. 2010; Ricci, Bellaby, and Flynn 2008; Sherry-Brennan, Devine-Wright, and Devine-Wright 2010; Emodi et al. 2021; Lozano et al. 2022). Meanwhile, negative opinions of hydrogen are usually linked to safety concerns and distrust of government, industry, or technology (Achterberg 2014; Zaunbrecher et al. 2016; Dumbrell et al. 2022). This in part explains why residents are, on average, less supportive of installing hydrogen export and storage infrastructure close to their own homes than they are of these technologies in the abstract (Zaunbrecher et al. 2016; Tarkowski and Uliasz-Misiak 2022; Lozano et al. 2022).[40]

Green hydrogen projects need to work with the communities to minimize socio-environmental and economic impacts; their production plans can draw on the frameworks of "energy justice" and the "just transition," which offer metrics to help make project planning and implementation more equitable.[41] Some lessons can be learned from previous renewable energy projects to avoid replicating undesirable impacts. Local socioenvironmental documented impacts of wind and solar projects among low income, minority, and indigenous communities include the use of land or resources previously used by communities; unfair or exclusionary planning processes; increases in existing social inequalities or vulnerabilities, particularly for indigenous groups; and ecological impacts (Sovacool 2021). These ecological impacts may include waste disposal (solar), habitat and land use (solar and wind), water table issues caused by the use of nonporous concrete (wind), and noise and light impacts (wind) (Levenda, Behrsin, and Disano 2021).

Efforts in northern Chile offer a roadmap for how energy justice could be more robustly incorporated into green hydrogen plans, prioritizing four elements:

- Inclusion of local stakeholders in planning and project design.
- Use of an integrated land-use planning process.
- Ensuring job predictions are accurate and training is provided.
- Long-term benefits to the community.

First, in addition to being transparent, planning processes can deliberately include local stakeholders, and this community input can be considered in project design. The participatory planning processes that Chile developed for its 2050 long-term Energy Roadmap (Alvial-Palavicino and Opazo-Bunster 2018) and just transition process (Ministerio de Minería de Chile 2021; Ministerio de Minería de Chile 2022, 45-46) offer promising models. In Antofagasta, regional officials held initial workshops to understand community hopes and concerns about green hydrogen in November 2022.

Second, advocates have argued that project-specific Environmental Impact Assessments or life-cycle analyses do not necessarily capture the cumulative impacts of hydrogen projects in regions where multiple projects are being planned simultaneously: An integrated land-use planning process is the most effective tool to assess and limit cumulative impacts (Comunicaciones 2022). In Chile, the drawing of Energy Development Poles offers one model: In this process, participatory workshops allowed stakeholders to identify areas with particular cultural significance or environmental sensitivity (Ministerio de Minería de Chile 2022a). This data was overlayed with technical data on land tenure, solar radiation, and transmission availability to identify recommended areas for renewable energy development. A similar process will overlay this social information with information now being collected about hydrogen production efficiency.

Third, policies can ensure that job predictions are accurate (including the anticipated contract period) and implement processes to ensure that people in the local communities receive the training needed to take these jobs. In Chile, as elsewhere, actual jobs in the solar and wind industry have consistently fallen below projections: Solar and wind jobs also tend to be short-term (e.g., installation of solar farms or wind turbines) (Ministerio de Energía de Chile 2022a, 60-62). One way that local universities and technical institutes can help address these challenges is by building flexibility into green hydrogen and renewable energy training programs, so that graduates are competitive for jobs in a range of industries.

Finally, projects to support community infrastructure and resources can help distribute long-term benefits to potential job users but also to communities, as multi-stakeholder roundtables have begun discussing through Chile's Socio-ecologically Just Transition initiative (Ministerio de Energía de Chile 2022a). This needs to be a priority.

Concluding Remarks

Chile is betting on green hydrogen to help meet its decarbonization goals and is creating a new industry, based on splitting the water molecule via electrolysis using renewable energy. Its natural resources of wind and solar power enable Chile to be at the vanguard of this new fuel. The market requirements for fertilizers, mining activity with heavy duty trucks, and transport are likely to support this green fuel at the same time as the country reduces its dependence on importing oil, natural gas, and coal. Governments and international agencies appear to support, both technically and financially, the development of green hydrogen.

The current global challenges to scale up the production of this new fuel among others include: 1) becoming cost competitive, 2) having the regulatory framework to create competitive markets, 3) developing the required infrastructure while attracting private sector participation and financing, and 4) developing global demand for hydrogen.

The potential identified challenges for hydrogen market development in Chile include:

- Access to low-cost renewable energy resources, and to competitive electrolyzer technology that allows producers to scale up operations and reduce production costs.
- An appropriate regulatory framework that 1) incentivizes demand for hydrogen (incentives to users, carbon pricing, quality/green certifications, and safety standards) locally and for exports, 2) incentivizes research and development to reach further technological advances, 3) incentivizes producers (fiscal policies and possible subsidies), 4) promotes crucial infrastructure development or allows for adequate updating, 5) sets open-access rules to allow for efficient use of infrastructure (pipelines, ports, etc.), 6) allows for the harmonization of standards to prepare for international trade.
- Community engagement to minimize future social discontent and guarantee benefits from this technology deployment. However, Chile already has legal instruments in place requiring "community participation in public policy" and specific energy policy provisions regarding the indigenous community.

In the medium term, demand for Chilean green hydrogen exports will depend on the speed of the global energy transition, and the ability to build the required facilities to handle green hydrogen or its derivatives. In the meantime, in addition to their vast number of bilateral trade agreements, Chile has worked extensively on their memorandums of understanding with key potential users of green hydrogen markets, i.e., Europe and Asia.

Multilateral and international organizations as well as governments and industry are providing funds to develop this clean fuel. The technology is being tested through pilot projects while local communities are being consulted about the impacts they may experience due to the location of these plants and the use of renewable energy sources.

Chile is powering ahead with plans to develop a green hydrogen ecosystem. The country is not only endowed with significant renewable resources, but also with critical minerals (such as copper and lithium) for the energy transition. Green hydrogen may help to make important economic activities greener in Chile:

- Greener oil refineries: by replacing gray hydrogen, which is currently used.
- Greener mining activities: by using derivatives (such as methanol) to replace diesel in heavy-duty transportation in mining activities, and by using green ammonia to produce explosives.
- Greener heavy and long-distance transportation: by using synthetic fuels to replace traditional fossil fuels in buses, trains, and heavy-duty trucks.
- Greener agriculture: by using green ammonia to produce fertilizers.

Renewable energy — like solar and wind power — makes it possible for countries like Chile to develop a competitive green hydrogen strategy. Chile's strategy is built with a medium- and long-term vision focusing first on decarbonizing the local economy and then becoming an exporter. Given its geography, coastal hydrogen hubs can be built to facilitate exports. Exports of hydrogen are planned to start in 2025 with Japan and Europe. By 2050, exports could reach Korea, China, the West Coast of the U.S., and Latin America. Export of hydrogen would start with ammonia and green hydrogen once technical, safety, and cost issues are resolved.

Regulatory changes and processes are evolving rapidly in Chile to facilitate the development of the new hydrogen industry while attempting to meet its climate goals. Regulatory transparency and simplifications are critical in this endeavor.

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Appendix

Table 4. Cost of Hydrogen By Production Process

Hydrogen Type	Source	Production Process	Cost	Considerations
Brown*	Coal	SMR	US$0.9/kg	About 139g CO2 eq per MJ
Gray**	NG	SMR	US$1.80/kg	Production cost for Europe is higher due to higher gas prices about US$2.4/kg
Blue**	NG	SMR + CC	CCS cost (US$0.55) = US$2.4/kg	Calculation does not consider carbon transportation and disposal
Green*	Water	Electrolysis	US$ 6-US$9/kg	Calculation does not consider water sourcing and transportation. No carbon footprint during production phase. Cost varies depending on electricity source (location).

Notes:

SMR: Steam Methane Reformer
CO_2 eq per MJ: Carbon Dioxide emissions equivalent per Mega Joule
NG: Natural Gas
CC: Carbon Capture, transportation and storage not included

Sources: *Mac Dowell, 2021, **Howarth 2021.

Table 5. Summary of Technical Features of Electrolyzer Technology, by Type

	AEL Alkaline electrolysis	PEM electrolysis	AEM electrolysis
Cathode (HER)	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Anode (OER)	$2OH^- \rightarrow ½ O_2 + H_2O + 2e^-$	$H_2O \rightarrow ½ O_2 + 2H^+ + 2e-$	$2OH^- \rightarrow ½ O_2 + H_2O + 2e^-$
Charge carrier	OH^-	H^+	OH^-
Electrolyte	Liquid electrolyte KOH	Acidic polymer membrane	Polymer membrane with diluted KOH
Temperature range	60-90 °C	RT - 80 °C	50-70 °C

Electrodes/Catalyst	Catalyst coated nickel substrates	Noble metals (platinum, iridium)	Platinum Group Metal (PGM) and non-PGM catalyst, nickel substrates
Typical current density	0.2- 0.6 A/cm²	1.0-2.5 A/cm²	0.5-1.5 A/cm² (at lab scale)
Technology Readiness Level (TRL)	8-9 (industrial mature)	7-8 (commercially available)	6-7 (field tests)
Typical pressure	atm. - 30 bar	atm. - 50 bar (350 bar)	atm. - 35 bar
Stack / module size	< 1,000 Nm³/h 0.5 – 2.5 MW_{el}	x-fold 100 Nm³/h 0.1 – 1.5 MW_{el}	Up to 0.5 Nm³/h < 2.5 kW_{el}
Specific electrical energy demand	4.2-5.8 kWh/Nm³ H2	4.5-6.8 kWh/Nm³ H2	4.8-6.9 kWh/Nm³ H2

Source: Holst et al. 2021, 16.

Table 6. Advantages and Disadvantages of Electrolyzer Technologies

	AEL	PEM	AEM
Advantages	• Mature, robust and proven technology • Multi-MW stacks enable systems with large capacities, already in operation today • Potential to use cheap and abundant materials	• Very high-power densities • Compact designs and small footprint • Fast cold start-up time, fast load changing capabilities • Suitable for high pressure operation • Stacks in MW range available • High intrinsic product gas purity	• Potential to use cheap and abundant materials means high cost-reduction potential • Compact designs and small footprint • Suitable for high pressure operation
Disadvantages	• High substantial material resistance on system level due to the highly alkaline/corrosive liquid as electrolyte • Low power densities and large footprint • Additional effort for gas purity required • Slow cold start-up time	• Use of expensive materials as titanium and critical platinum group metals (PGM) on cell level • long-term stability needs to be proven at MW-scale	• Low technology readiness level, only few commercial systems available • Limited long-term stability

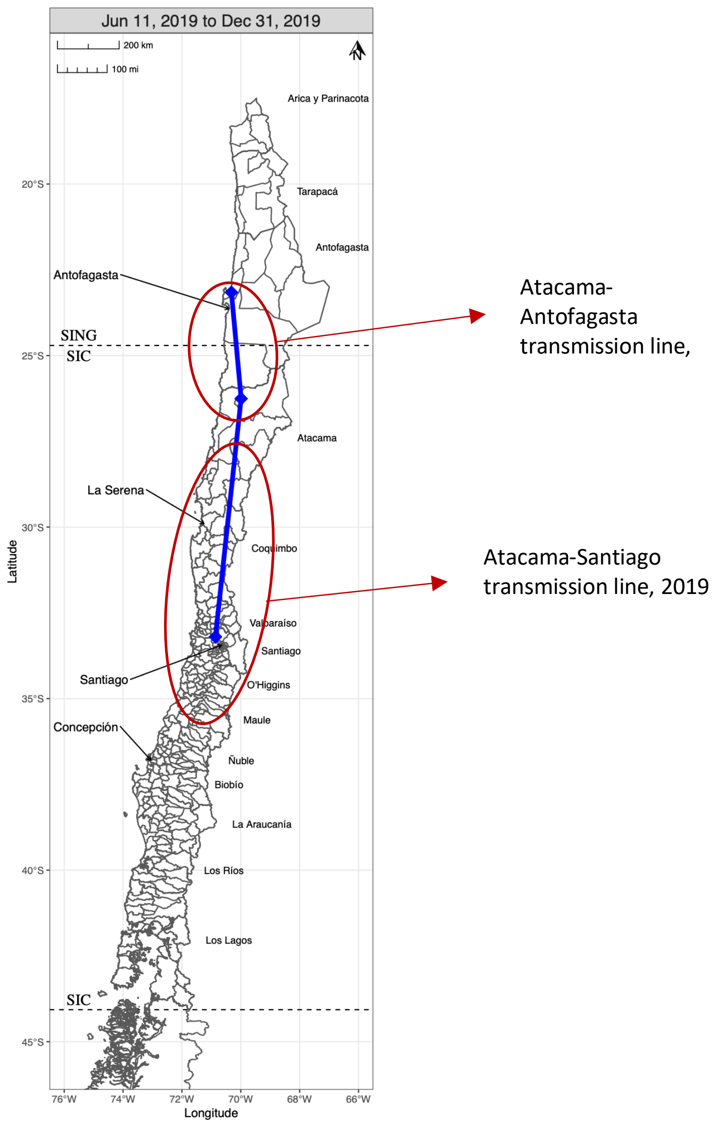
Source: Holst et al. 2021, 17.

Table 7. Required Hydrogen Pressure by Application

Application	Pressure (bars)
Pipeline injection	60-100
Underground storage (cavern)	<200
Hydrogen Refueling Station	350-900
Ammonia production	~200

Source: Holst et al. 2021, 37.

Figure 14. Grid Expansion in Chile



Source: Gonzales, Ito and Reguant 2022.

Table 8. Existing Regulations in Chile That Apply to Hydrogen

Type of regulation	Institution	Existing regulation
General	Ministry on Energy	Law No 21305 — Law of Energy Efficiency
	Ministry on Energy	Law 21.505 — Law that Promotes Electrical Energy Storage and Electromobility
Hydrogen as a dangerous substance		
Safety	Ministry of Health	Decree 43, 2016: It regulates the storage of dangerous substances such as hydrogen, but it excludes liquid and gaseous fuels used as energy sources. Exempt resolution RE 408/MINSAL 2016: Introduces hydrogen as a dangerous substance in both its compressed and liquid forms. Decree 594, 2018: It regulates the basic sanitary and environmental conditions in workplaces.
	Ministry of Transport and Telecommunications	Decree 298, 1994: it regulates the transport of dangerous cargo in public spaces. Resolution RE 96, 1997: it updates and modifies the regulation on handling and storage of dangerous cargo in port facilities.
	Ministry of Labor and Social Security	Decree 40, 1995: regulation on the prevention of professional risks.
	Ministry of Mining	Decree 132, 2004: It regulates mining safety.
		In process: — Safety rules for hydrogen installations. — Hydrogen quality specifications. — Regulation of fueling service stations. — Regulation of multifuel installations.
Standardization	National Institute for Standardization (INN)	NCh382.Of98, 2017: Official norm of dangerous substances, terminology and classification. NCh2245.Of2015, 2015: Safety data sheet for chemical products. NCH2190.Of2003, 2003: Transportation of dangerous substances — badges/signs for risk identification. NCh1411/4.Of78: Risk prevention - Part 4: safety signs for the identification of material risks.

Source: Based on Centro Energia UC (2020, 32) and H2LAC.

Table 9. Administrative Procedure Schedule for Applications to Direct Concessions for Green Hydrogen Projects

Milestone	Deadline
Announcement and opening of the consultation period	November 23, 2021
End of consultation period	December 17, 2021
Responses to queries made	December 31, 2021
Opening of a single window for receiving applications	January 3, 2022
Single window closure	January 14, 2022
Analysis of requests, cadastral validations, relevance analysis and conflict resolution due to possible overlaps	February 25, 2022
Regional Processing: Preparation of plans, enrollment, internal appraisal, external appraisal, processing before the Special Commission for Disposals, delivery of the guarantee of seriousness of the application and submission of the file to the Central Level.	Between the months of October 2022 to February 2023
Central Level Processing: Review of background information, issuance of authorizing decree, publication of the extract from the authorizing decree in the Official Gazette and preparation of the Contract.	Between the months of March 2023 to May 2023
Contract signing	Between the months of May and June 2023
Decree approving the contract	Between the months of June and July 2023

Source: National Plan for the Promotion of Green Hydrogen Production in Fiscal Territory. Available at the website of the Ministry of National Assets, https://www.bienesnacionales.cl/?page_id=41049.

Acknowledgments

We would like to acknowledge Caroline White-Nockleby for her valuable research support, as well as Santiago Ariza and Bikram Singh for their research assistance. We are also thankful to Gino Cruz Olmeño (from Universidad Andrés Bello of Chile), Ken Medlock, Michael Maher and Michelle M. Foss for their helpful comments.

Endnotes

[1] Net zero is reached when the amount of greenhouse gases going into the atmosphere are balanced by the amount removed of the atmosphere, by reducing emissions and implementing ways of absorbing carbon dioxide.

[2] By 2019 in South America, agriculture and land use account for 53% of the region's greenhouse emissions, followed by transport, with 13% (for more information see Our World in Data).

[3] According to the Global Carbon Project, by 2021, South America produced 1.07 billion tonnes, one of the lowest regional carbon emissions. Only the US produced around 4.7 times the carbon emissions from South America, the same year. See https://ourworldindata.org/co2-emissions for more detailed information.

[4] "Energy matrix" refers to the combination of primary energy sources used within a geographic region to meet its energy needs.

[5] For detail see United Nations Climate Action page.

[6] IEA 2022d solar PV may account for 60% of global renewable power growth in 2022, followed by wind and hydropower.

[7] Hydrogen is also known as an "energy carrier" because it does not exist freely in nature and is produced only from other energy sources (National Renewable Energy Laboratory n.d.).

[8] One kilogram of hydrogen contains 39.4 kWh of usable energy at higher heating value, and 33.3 kWh at lower heating value (appendix G of NRC and NAE 2004).

[9] According to Antonio Fayad (from EDP renewables), the estimated costs shares of electricity and electrolyzers were 59% and 20%, respectively (Fayad 2022).

[10] PEM electrolyzers need low levels of partial load (from 0 to 10% of design capacity) compared to the other technologies (AEMs require 10-20% of design capacity), and respond well and quickly to rapid cycling in flexible operational conditions, so they are suitable for electricity grid-balancing services (Patonia and Poudineh 2022a).

[11] High load factors are key to producing cheap hydrogen. The load factor in Europe varies around 15%-19%. By 2021, the capacity utilization factor of solar PV in the U.S. was 24.9%, and by 2015, in India it ranged between 15% to 19% (see https://www.energy.gov/ne/articles/what-generation-capacity.

[12] The levelized cost of energy (LCOE) measures the lifetime costs for a generator divided by energy production. Used for investment planning, it is a way to compare different methods of energy generation.

[13] For further detail see the Renewable Power Generation Costs in 2021 from IRENA.

[14] Most electrolysis systems allow a maximum feed water conductivity of 1 µS/cm (Holst et al. 2021).

[15] The usual water source for electrolysis is tap water (typically 100-1,000 microsiemens per centimeter µS/cm from public grids) because it is relatively cheaper, its supply is stable, and it may face less intensive regulatory requirements. However, tap water usage for hydrogen generation requires double the amount of water compared to using demineralized water (between 1 to 2 liters per 1 Nm3 — normal cubic meter — of hydrogen produced) due to the requirements of the reverse osmosis system (Holst et al. 2021).

[16] Woods et al. (2022) offer one possible solution, demonstrating that Australia could use wastewater and tertiary water effluents (wastewater) with little additional treatment, generating an environmentally sustainable "circular" water source for electrolysis.

[17] Mining companies are big users of desalinated water. In fact, by 2022, close to 75% of the desalinated water in Chile was used by mining activities (Tapia 2022).

[18] Information retrieved on January 15 2023 from https://forbes.cl/sostenibilidad/2022-11-11/convenios-de-financiamiento-para-proyectos-de-hidrogeno-verde-en-chile-se-firmaran-este-viernes-en-la-cop27/.

[19] For more information, see the H2Chile website.

[20] For more information see the H2LAC website.

[21] For more information see Corporacion Alta Ley website.

[22] The 27th Conference of the Parties: see https://cop27.eg/#/.

[23] Qualified clean hydrogen is "hydrogen which is produced through a process that results in a lifecycle greenhouse gas emissions rate of not greater than 4 kilograms of CO2e per kilogram of hydrogen" (Inflation Reduction Act of 2022, Section 13204).

[24] See Bezos Earth Fund, accessed on November 30, 2022.

[25] In January 2021, the Norwegian electrolyzer manufacturer Nel announced plans to reduce the costs of its PEM electrolyzers by 75% by 2025. Similarly, in July 2022, the European electrolyzer manufacturer Enapter announced an 83% cost reduction of its AEM Electrolyzer by 2025, reducing the price of ts electrolyzers to € 550/Kw.

[26] According to a 2013-2014 census of mining equipment, there were 1,592 trucks operating in open pit mines in Chile.

[27] This figure is consistent with the Rocky Mountain Institute's calculations: According to the RMI, each mining haul truck consumes roughly 900,000 liters of diesel per year and these trucks make up 30%-50% of their mines' total energy use (Muralidharan et al. 2019).

[28] Chile is one of the countries most open to international collaboration; by 2019 it had 22 preferential trade agreements, 20 of which are bilateral (Licetti et. al 2020).

[29] According to Samsun et al. (2022), by the end of 2021 the total global fleet of FCVs (which includes passenger cars, vans, buses, and fuel cell trucks) was over 50,000 units, 91% of them in four countries: South Korea (38%), USA (24%), China (16%), and Japan (13%). Also, around 82% of all the FCVs are passenger cars (fuel cell electric vehicles or FCEVs), 9.4% are fuel cell buses, 7% medium-duty trucks and 1.7% heavy duty-trucks. China has the largest number of FCBs (88%), medium-duty trucks (98%) and heavy-duty trucks (93%).

[30] The concept of a "hydrogen hub"— a cluster of hydrogen projects in a single area, ideally located near port infrastructure to facilitate export — can help planners and regulators maximize shared infrastructures and economic synergies across multiple projects and can encourage hydrogen users to locate in or near the hub, resulting in shorter transport distances.

[31] In 2019, the Chinese company Geely launched the FARIZON AUTO M100 Methanol Heavy Truck, thus introducing the option to use methanol as a substitute for diesel in heavy transportation. See https://www.methanology.com/GeelyTrucks.

[32] More details can be found at https://www.goreantofagasta.cl/aspectos-economicos/goreantofagasta/2016-09-26/095739.html.

[33] For more information see news alert about Energy Efficiency Law implementation in Chile at https://www.garrigues.com/es_ES/noticia/chile-avanza-implementacion-ley-eficiencia-energetica.

[34] In October of 2020, the Ministry of National Assets agreed to reserve 11,986 hectares for green hydrogen projects in Atacama (Diego de Almagro). See https://www.bienesnacionales.cl/?p=38741.

[35] This stage should last at most five years, and it starts with the contract subscription, and ends with a favorable Resolution of Environmental Qualification (RCA for its Spanish name *Resolucion de calificacion ambiental*).

[36] In this stage the concessionaire needs to obtain all missing sectorial licenses and complete the project construction; this stage ends with the registration of the project to the SEC Registry of installations associated with the hydrogen supply chain.

[37] In this stage the concessionaire must run its operation guaranteeing a minimum of 20 MW of electrolyzer capacity within the first two years of operation.

[38] A few recent articles examine public perceptions of underground hydrogen storage (for review, see Tarkowski and Uliasz-Misiak 2022) and large-scale hydrogen production for industry or export, the latter primarily in the Australian context (Chapman, Fraser, and Itaoka 2017; Lozano et al. 2022; Dumbrell et al. 2022).

[39] A recent study in Japan, for instance, found that stakeholders wanted planned hydrogen generation projects to be used to meet regional energy needs, and to help improve local access to affordable and reliable energy, rather than for export (Trencher and van der

Heijden 2019). The extent of projected job opportunities for locals can also affect public support (Dumbrell et al. 2022; Lozano et al. 2022).

[40] In a survey of 2,785 Australian residents about their views on hydrogen, Lozano et al. (2022) found that while nearly three quarters of residents would support the development of a hydrogen export industry in Australia, only 38% of respondents would be supportive of a hydrogen export facility being built nearby.

[41] "Energy justice" evaluates energy projects according to three types of justice: procedural (inclusive, democratic planning processes), recognition (recognizing and acting on the experiences, knowledge, and interests of historically marginalized communities), and distributional (equitable distribution of costs and benefits) (e.g., Heffron and McCauley 2017). The "just transition" seeks to leverage low-carbon transitions to address socioenvironmental inequities, particularly among workers and communities impacted by fossil fuel closures and renewable energy projects (e.g., Evans and Phelan 2016). Scholars and policymakers have begun to adapt these tools to green hydrogen (e.g., Chapman, Fraser, and Itaoka 2017; Werker, Wulf, and Zapp 2019; Chu et al. 2022; Swennenhuis, de Gooyert, and de Coninck 2022).