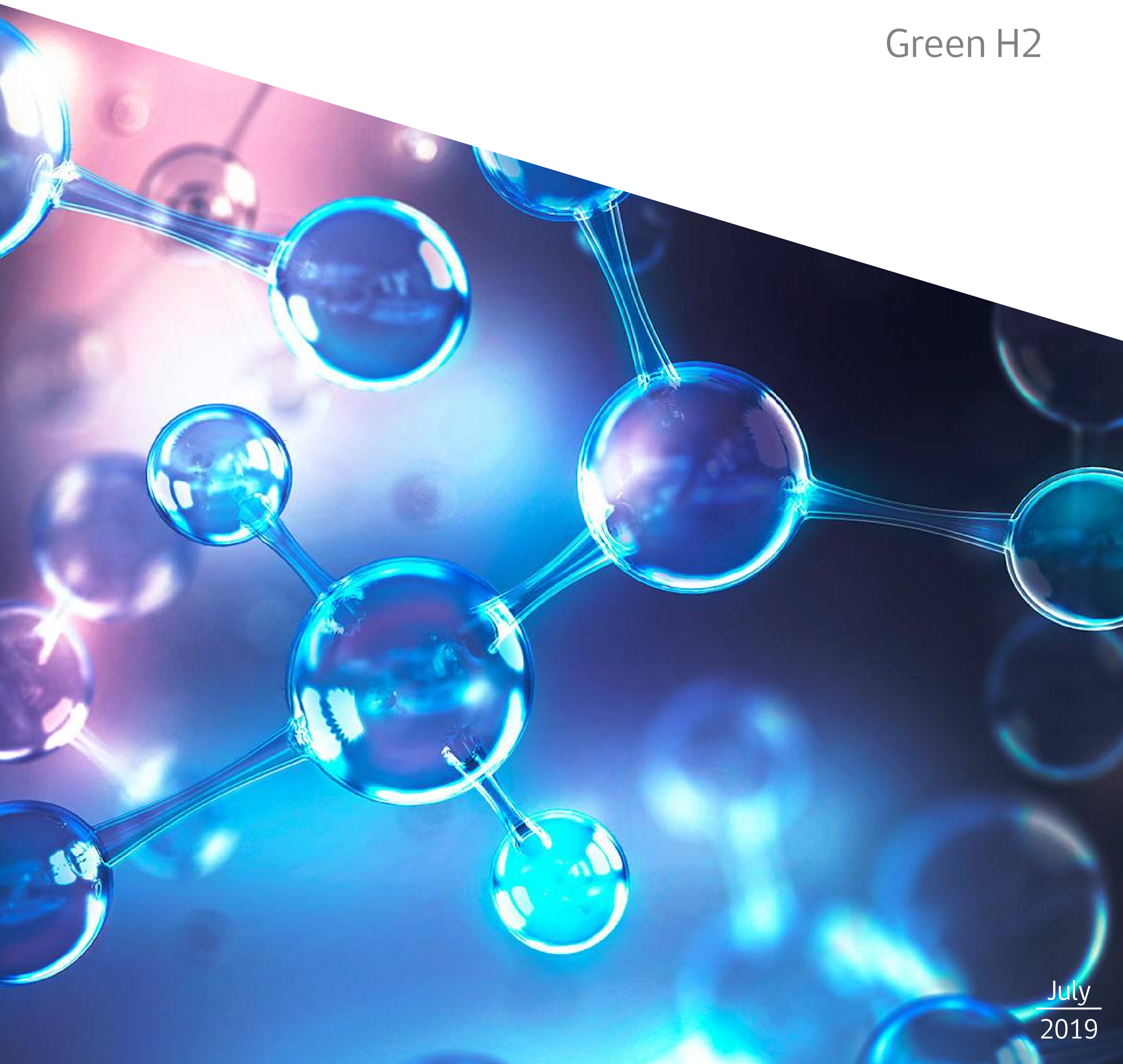
COMITÉ SOLAR E INNOVACIÓN ENERGÉTICA | CORFO | Ministerio de Energía, Gobierno de Chile | Chile en marcha

Green hidrogen

National strategy proposal to stimulate the market in Chile

Green H2



July

2019

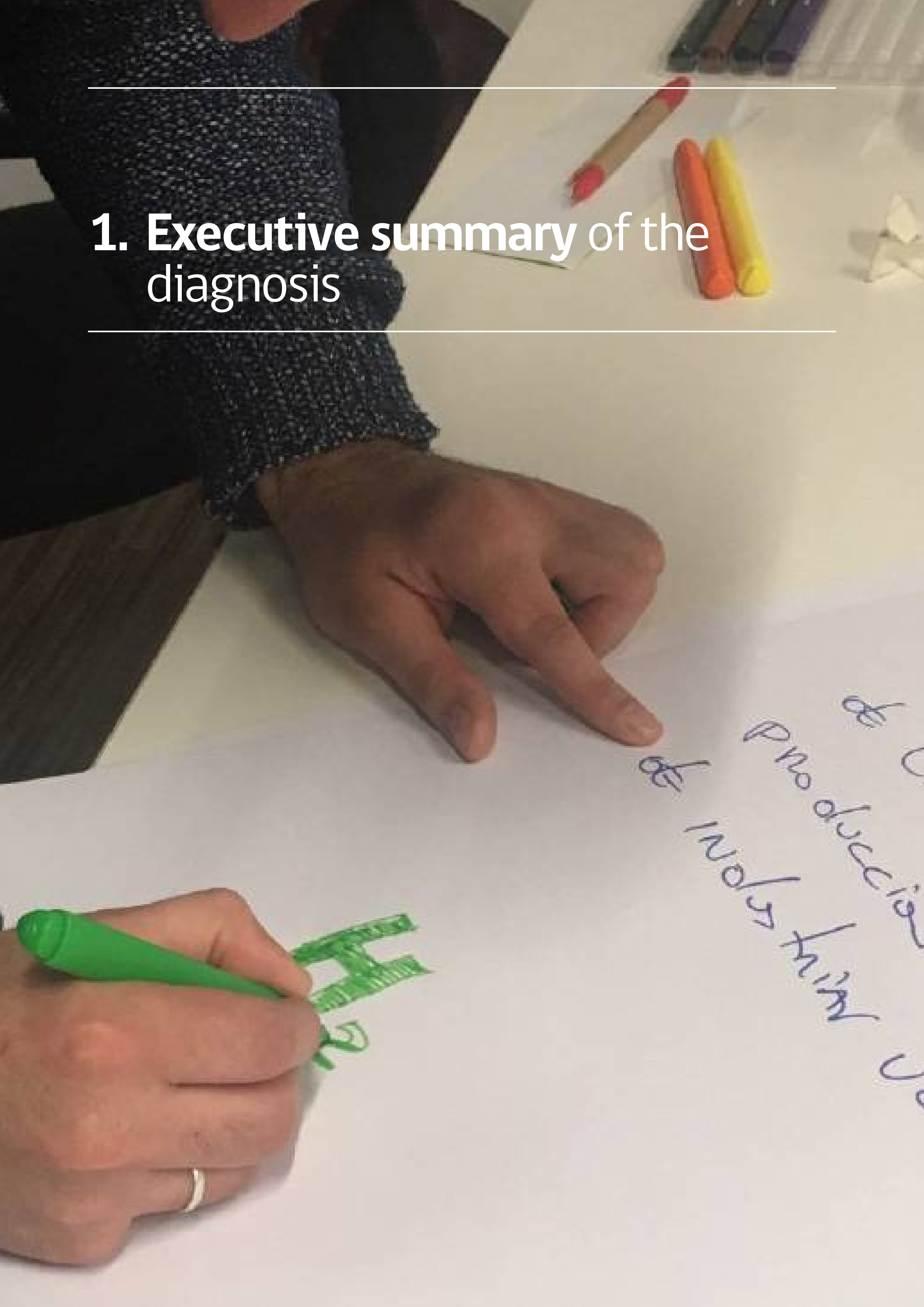
Green hidrogen

National strategy proposal to stimulate the market in Chile

Green H2

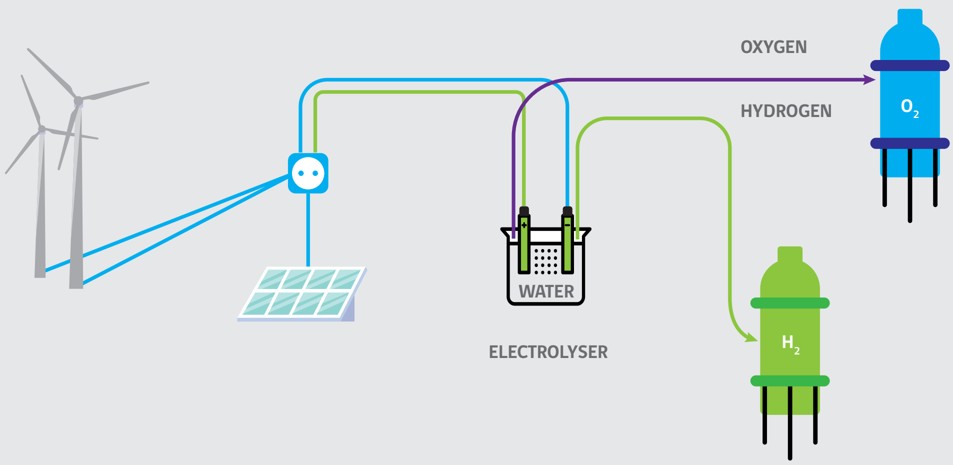
COMITÉ SOLAR E INNOVACIÓN ENERGÉTICA | CORFO | Ministerio de Energía Gobierno de Chile | Chile en marcha

1. **Executive summary** of the diagnosis



The energy sector contributes around 77% of the total national greenhouse gas emissions of Chile (Ministry of Energy, 2017), and the decarbonization of this sector is key to emissions mitigation efforts in the country. A promising approach for meeting the challenge of decarbonizing the country's energy matrix is to take advantage of the abundance and low costs of renewable energy sources to generate electricity at competitive prices. Renewable energy generation serves not only to supply electricity but also to produce hydrogen gas (H2), an energy carrier that has several different applications. Some 95% of H2 production is currently based on thermal processes using hydrocarbons (natural gas, liquefied petroleum gas or naphtha), which have associated CO2 emissions. However, it is also possible to produce H2 through the electrolysis process, using just electricity and water as inputs. In this process, which requires an electrolyser, an electricity current is applied to water, separating it into oxygen (O2) and hydrogen (H2):

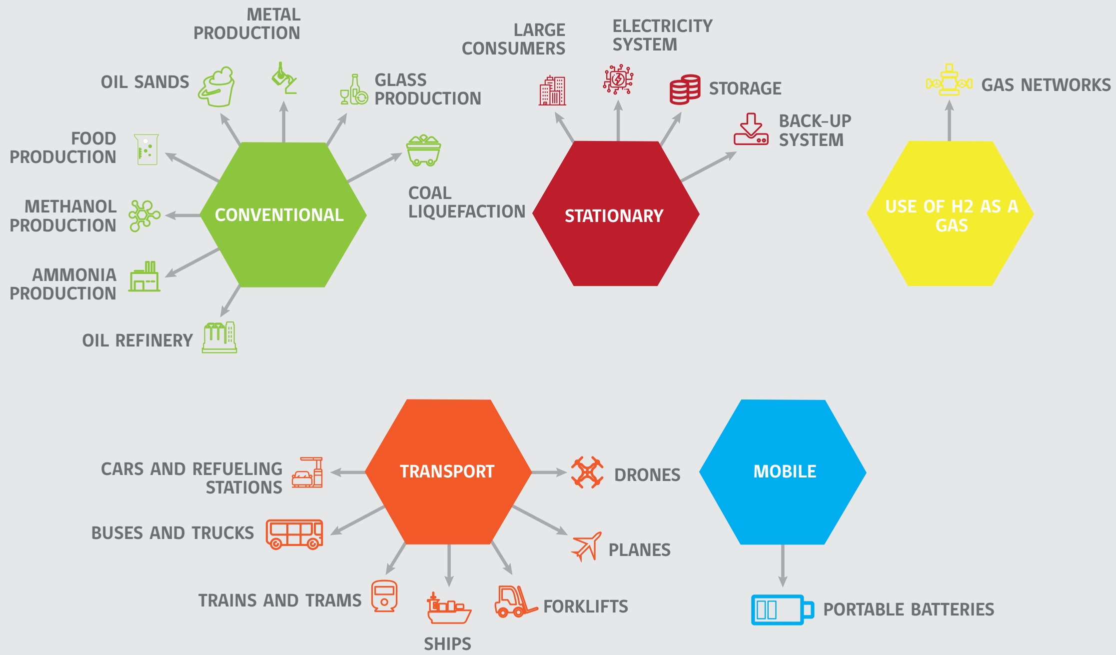
FIGURE 1: ELECTROLYSIS PROCESS FOR THE PRODUCTION OF HYDROGEN



Source: HYDROGEN COUNCIL

By making use of electricity from renewable sources, CO_2 emissions are avoided in the production of hydrogen and this is considered to be "green". Green hydrogen produced in this way is versatile in terms of its possible applications: it can be used as an industrial raw material (for example, as an input for the production of glass, metal, foods like margarine, oil refining processes); for heat supply (combusted alone or mixed with natural gas, or for the production of cleaner methane); as fuel for mobility purposes in various transport sectors, using cells fuel that convert H_2 gas into electricity; for the production of cleaner Ammonia (NH_3) as an input for the production of fertilizers and explosives. In addition, this green H_2 serves to store energy in large quantities and over long periods of time, for example by injecting it into existing natural gas networks. This helps to stabilize energy, whose supply variability has increased with the growing share of renewable energy in the electric matrix.

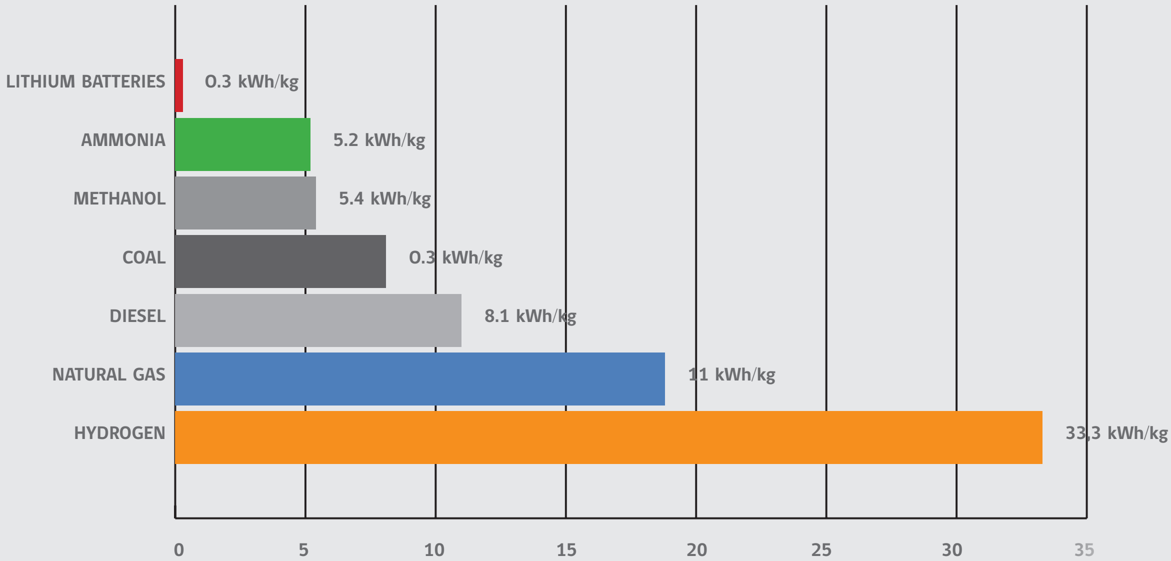
FIGURE 2: USES FOR HYDROGEN



Source: GIZ (2019)

The main benefits of using green hydrogen in these different sectors lie in the replacement of fossil fuels, and their associated CO2 emissions. This supports the decarbonization of sectors in which green hydrogen is introduced and, due to this replacement, increases independence from fossil fuel imports from other countries. In the use of green hydrogen as a mobility input, through fuel cells, greater autonomy is achieved for the transport mode compared to conventional fossil fuels, because of the very high gravimetric energy density of hydrogen (three times greater than diesel):

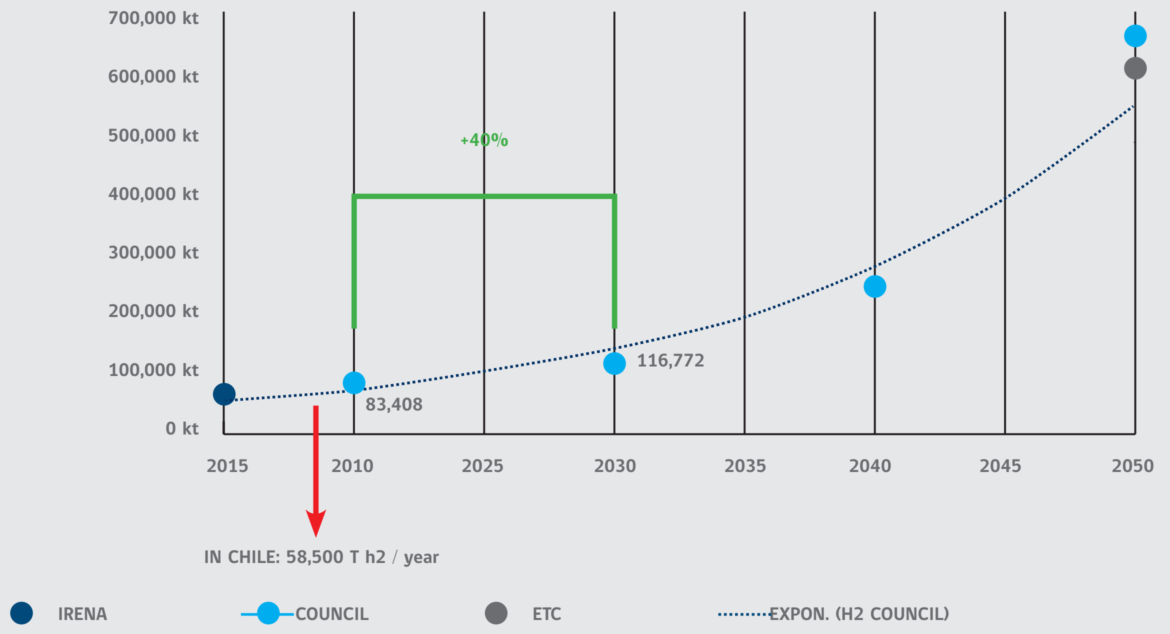
FIGURE 3: COMPARISON OF GRAVIMETRIC ENERGY DENSITY (KWH/KG)



Source: LEHMANN (2014, p. 75); FRAUNHOFER ISI (2015, p. 11)

Globally, many countries are currently considering hydrogen as an alternative to the use of fossil fuels, to decarbonize their energy matrices and become more sustainable societies. While technologies for its production already exist, economies of scale are still required for this to become economically feasible. The ambitious goals for hydrogen production (green) and use and financial investments that the governments of Japan, Australia and South Korea and making, among others, are setting the development pace of the market internationally. Due to this, several international bodies project a high growth rate for the global H2 market, from the current 83.4 million tons (2,200 TWh), according to IRENA (2018), to 116.72 million tons by 2030:

FIGURE 4: EXPECTED GROWTH IN THE GLOBAL H2 MARKET



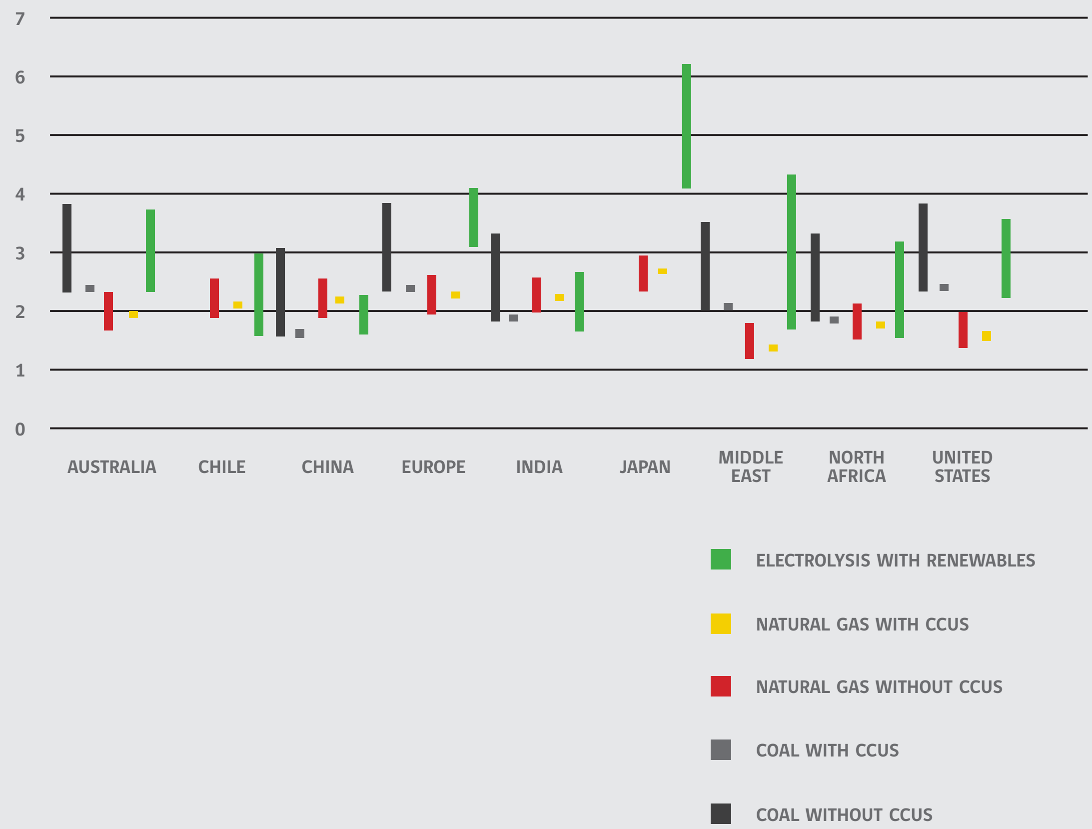
Sources: IRENA (2018, p. 31); HYDROGEN COUNCIL (2017, p. 20); ETC (2018, p. 22).

Why is green hydrogen a promising market opportunity for Chile?

Chile, owing to the vast, well-known renewable energy resources throughout the country, which amount to 1,384 GW (Ministry of Energy, 2019), has a major advantage in comparison to other countries. The relatively low costs of renewable energy production, particularly of solar, due to high levels of irradiation, and wind energy, due to to high plant factors, mean that Chile has the potential to become a large-scale producer of green hydrogen. On the one hand, this can support the decarbonization of Chile's own energy matrix and reduce dependency on fossil fuel imports, and on the other hand, it can provide hydrogen to countries like Japan who have a planned demand for this energy carrier.

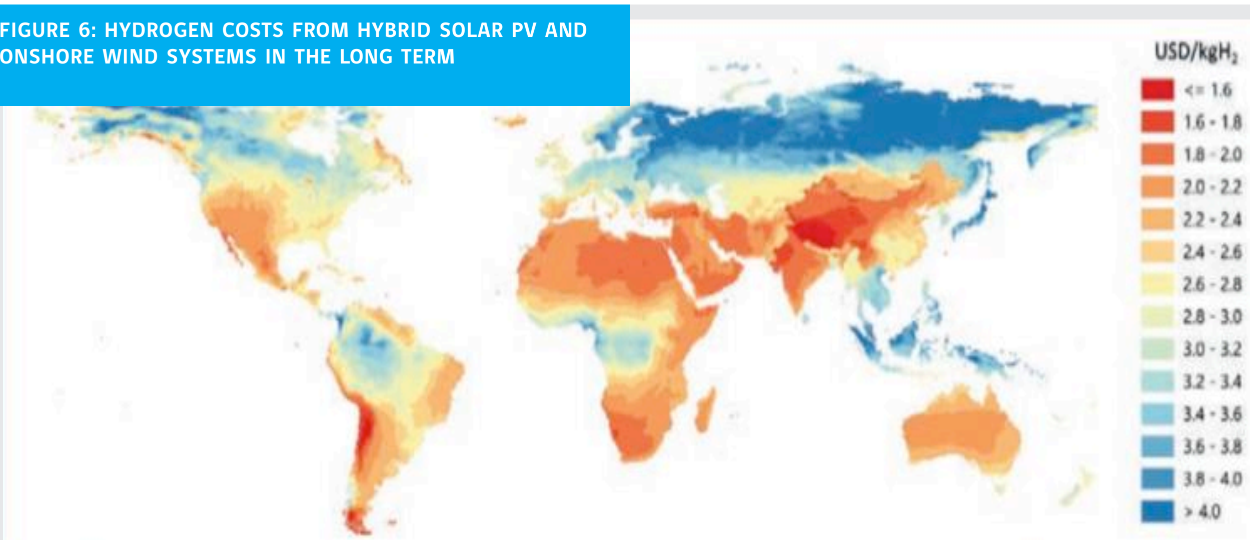
As the following two graphs show, prepared by the International Energy Agency (IEA, 2019), green H2 can be produced in Chile through electrolysis fed by renewable energy at costs of less than 1.6 USD / kg; values which are cheaper than Australia, a country that seeks to supply the demand, clearest today, in Japan:

FIGURE 5: COMPARISON OF HYDROGEN PRODUCTION COSTS (IN GREEN IS PRODUCTION THROUGH ELECTROLYSIS FED BY RENEWABLE ENERGY]



Source: IEA (2019)

FIGURE 6: HYDROGEN COSTS FROM HYBRID SOLAR PV AND ONSHORE WIND SYSTEMS IN THE LONG TERM

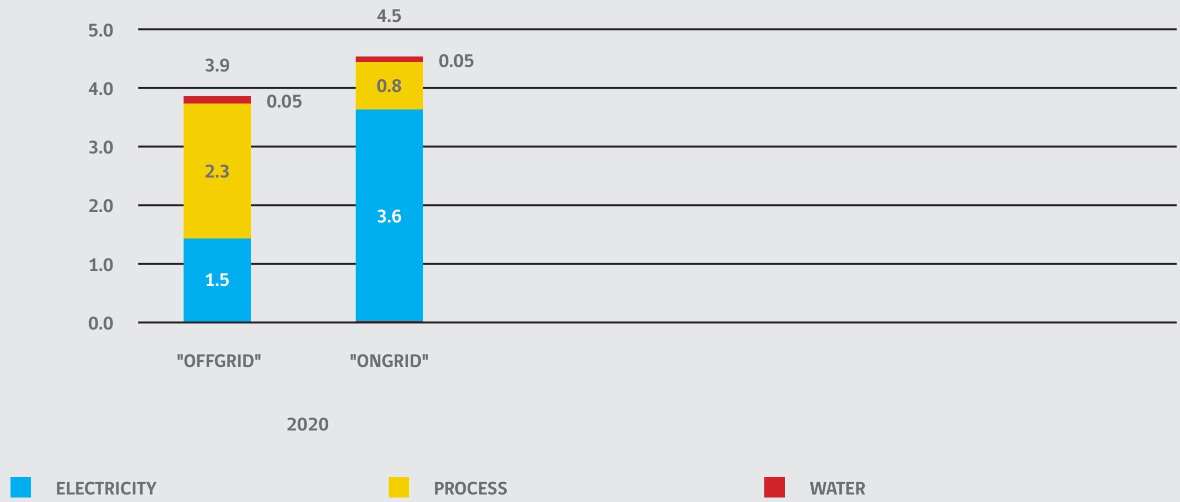


Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Electrolyser CAPEX = USD 450/kW$_e$, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8%.

Source: IEA analysis based on wind data from Rife et al. (2014), *NCAR Global Climate Four-Dimensional Data Assimilation (CFDDA) Hourly 40 km Reanalysis* and solar data from renewables.ninja (2019).

According to calculations produced as part of this project, the following green H2 production costs (USD / kg) can be achieved in Chile, differentiating between a production plant (electrolyser) connected to the electricity network (on-grid) and one that is disconnected (off-grid).

FIGURE 7: COMPARISON OF COSTS OF PRODUCING HYDROGEN THROUGH ELECTROLYSIS (INCLUDING INPUTS, USD/KG OF HYDROGEN)



Source: PRODUCED BY THIS PROJECT, BASED ON THE STUDIES CONSIDERED IN THE PREVIOUS STEPS

As the graph indicates, the main factor that determines the cost of green hydrogen is the cost of electricity. This is lower where it is provided by production plants not connected to the network, since this avoids transmission costs and complementary services that are existing components of the network electricity price. Another benefit of producing green H2 in an off-grid production plant is that, due to the use of 100% renewable electricity, the emissions factor is null, as compared to the emissions factor of the national power grid, which is still largely powered by fossil energy sources. The price of water is the component with the least influence on the production price, since only around 8.9 liters of water / kg H2 are required.

With green H2 replacing fuels fossils, fuel hydrotreating processes in Chile's refineries could reduce their CO2 emissions intensity, just as in the case of industrial metallurgical, glass and food production. A mixture of natural gas with hydrogen in gas power plants (co-firing) would help decarbonize the energy matrix, as would the use of hydrogen as a fuel for transportation, as is already being promoted in the state of California (USA), above all for long distance and heavy load purposes. A further highly relevant application would be in mining.

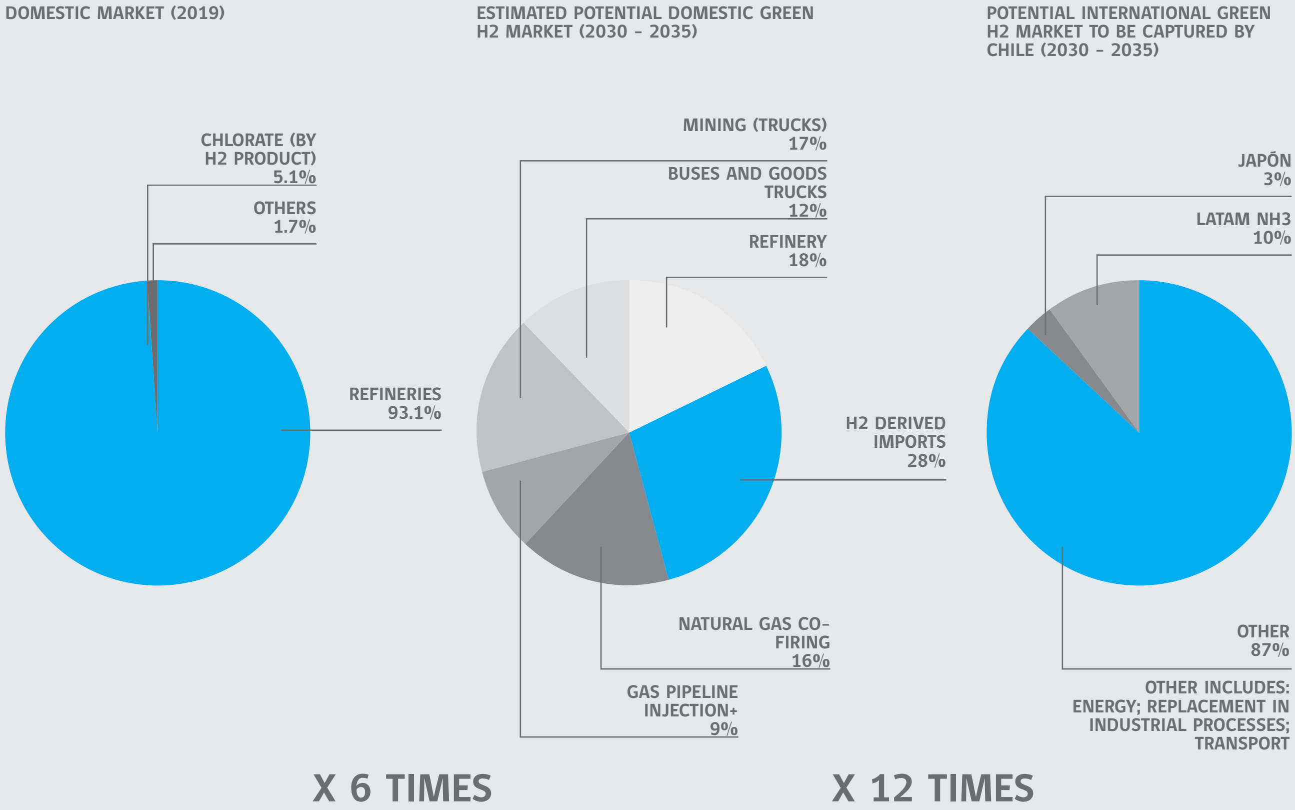
The growing share of renewable energy in the Chilean energy matrix increases variability in the level of supply, due to periods of time with less (or no) solar irradiation or less wind. At times, supply also exceeds demand. To take advantage of, and not waste, the energy generated, and to create reserves to address possible gaps in supply, energy storage solutions are required. One solution may be to store hydrogen in gas pipelines (existing infrastructure) or cavities underground. This allows the storage of energy in large volumes and over the long term. This so-called "Power-to-Gas" process is being analyzed in several countries, in particular regarding the potential percentages of H2 that can be mixed with NG for regular gas supply. This currently ranges around 10%, with interest in increasing this percentage to 20% (for example, in Germany).

Another important factor that makes green hydrogen production attractive for Chile is the high demand for ammonia (NH3) in the Latin America region; mainly used (88% worldwide) for the production of agricultural fertilizers. Ammonia is one of the most commonly produced synthetic chemicals in the world, and its production requires hydrogen as an input. The production of explosives, for example for mining, also requires NH3. The main explosives producer in Chile, Enaex, is currently importing 360,000 tons of NH3 per year from countries like Trinidad and Tobago (Caribbean). These imports could be replaced by the national production of NH3 through green hydrogen produced in Chile. This also opens the potential for Chile to export green ammonia and fertilizers. In addition, ammonia is a good means of transport for H2, since liquefaction of NH3, at -33°C occurs at less low temperatures as H2 (-252°C) and technologies for its transportation already exist.

A recent IEA study (Armijo, J., May 2019) demonstrated the high potential for hybrid solar-wind plants to produce green hydrogen and ammonia, based on detailed modeling analysis that included locations in Taltal, Calama, and Chilean and Argentinian Patagonia. According to this study, this type of hybrid plant can produce green NH3 at a 5% lower levelized cost of ammonia (LCOA), and green H2 could be produced at costs ranging from 1.96 - 2.35 USD / kg H2, cheaper than traditional production alternatives based on fuels fossils.

Considering all of the potential uses and demands for green hydrogen described, and assuming realistic growth scenarios for demand and investment in innovative technologies, it has been estimated by this current project that there is significant potential for national market growth towards the year 2030/35:

FIGURE 8: GROWTH PROJECTIONS FOR THE GREEN HYDROGEN MARKET IN CHILE



2019	2030 NACIONAL	2030 INTERNACIONAL
58,500 t H2 / year 123 MUSD / year 2019, assuming cost of 2.1 USD / kg H2	325,615 t H2 / year 684 - 749 MUSD / year by 2030 (market value produced), assuming costs of 2.1 - 2.3 USD / kg H2	3,850,000 t H2 / year 8,081 - 8,851 MUSD by 2030 (market value produced), assuming costs of 2.1 - 2.3 USD / kg H2
PV INSTALLED TODAY: ZERO (2.4 GWP IN SEN)	**ADDITIONAL PV CAPACITY INSTALLED: 7.1 GWP (4,700 MUSD, ASSUMING PV CAPEX OF 657 USD / KWP)**	**ADDITIONAL PV CAPACITY INSTALLED: 84.4 GWP (55,000 MUSD, ASSUMING PV CAPEX OF 657 USD/ KWP)***

*** Size-comparison with mining: portfolio of projects with investment of 65,747 million USD from 2018 to 2027 (Source: Ministry of Mining, Chile).**

According to this estimate, the current domestic market of 58,500 tons of H2 / year, with 99% demanded by the oil refinery industry, could grow to about 325,615 tons of H2 / year by 2030. This assumes, for example, a 10% replacement of conventional extraction trucks in mining with dual diesel and hydrogen fuel engines, along with other assumptions for each sector, as indicated by the following table:

TABLE 1: ESTIMATED NATIONAL TECHNICAL POTENTIAL FOR GREEN HYDROGEN BY SECTOR, UP TO 2030/35

	TOTAL NATIONAL MARKET	**ESTIMATED PENETRATION**				
USES	**GWh / year**	**%**	**GWh / year**	**t / year**	**MMUS$**	
REFINERY	1,950	100%			123	
IMPORTS DERIVED FROM H2	3,000	100%			189	NH3 for fertilizers and ammonium nitrate
CO-FIRING GAS PLANTS	29,379	6%			111	Considers pipeline limits without increased investment
GAS NETWORK INJECTION	17,000	6%			64	Considers pipeline limits without increased investment
MINING (TRUCKS)	18.,478	10%			116	Considers 10% penetration
BUSES AND TRUCKS		10%			80	Considers 10% penetration
					684	

Source: PRODUCED BY THIS PROJECT.

2. **Proposed** national strategy for green H2

DRIVERS

For the development of the strategy proposal, a series of participatory workshops were held in the cities of Santiago, Concepción, Antofagasta and Punta Arenas. This brought together the visions and proposals of more than 200 professionals nationwide.

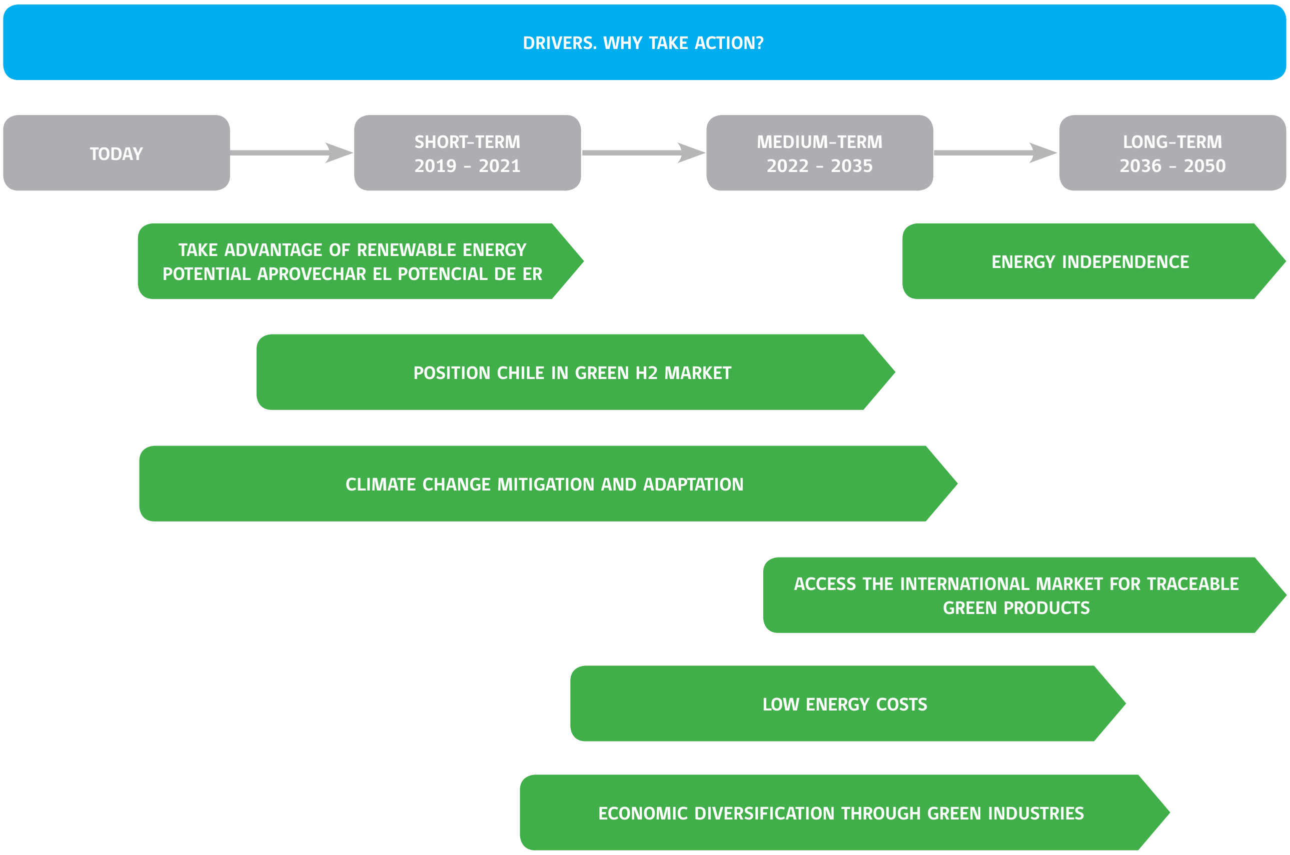
Based on the information gathered in the workshops, several different drivers are seen as important for the creation of the strategy, and these are elements that will mobilize stakeholder action.

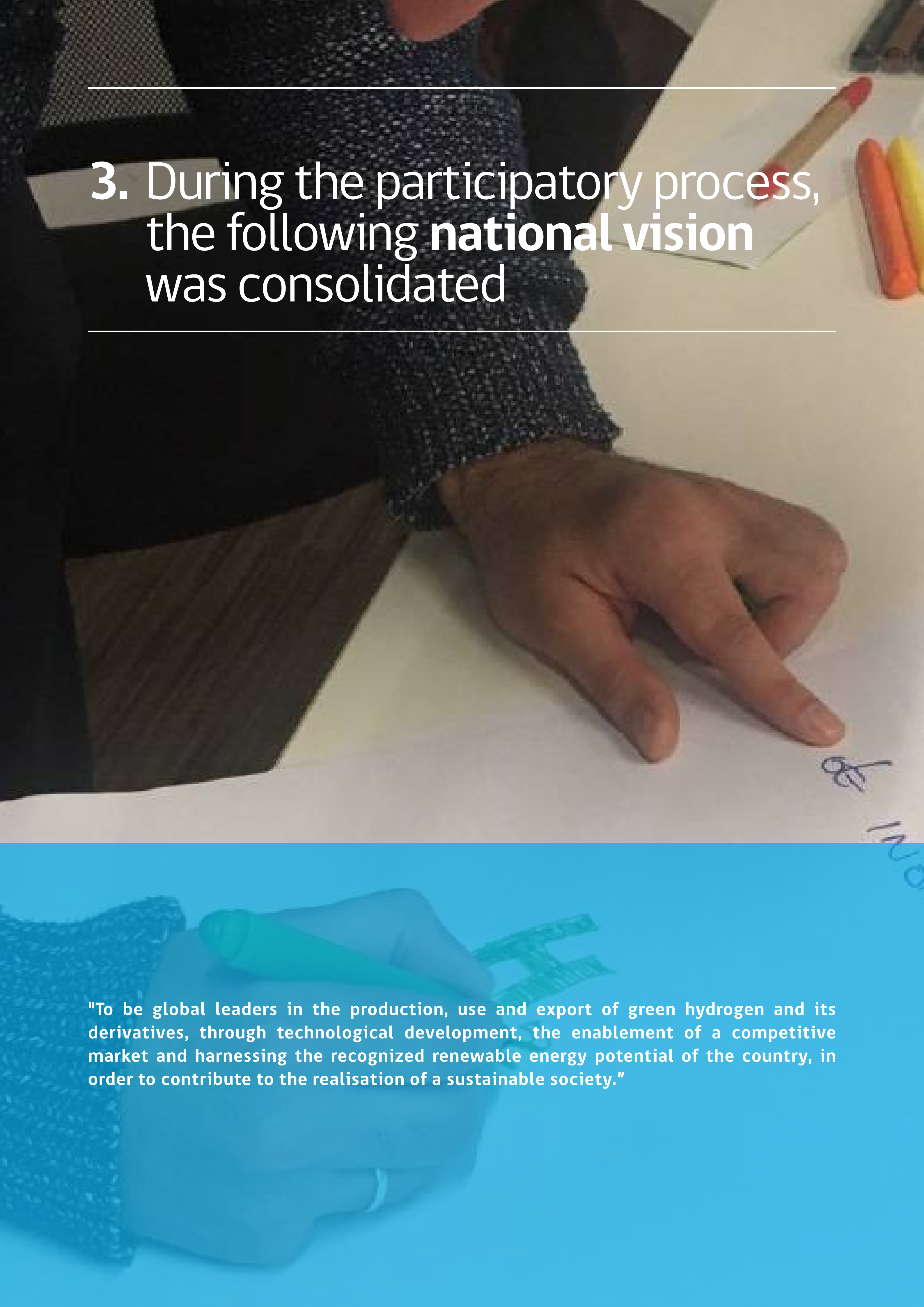
As an immediate or short-term driver, the great potential of renewable energies at the national level was identified, which is consistent with the opportunity that the production of green hydrogen generation offers. Arising from this is also the driver of "[positioning] Chile in the green H2 market", which links the potential of renewable energy generation, with the possibility of capturing new business opportunities.

Climate change mitigation and adaption, emerged as a short- and medium-term driver, and is associated with the chance to promote the use of clean energy and of reduce emissions. This in turn is seen as an opportunity to support change in different industries, by providing low carbon energy. Additionally, as a driver in the long term, is "energy independence", which is associated with the opportunity for economic development driven by the proliferation of renewable energy.

The global trend for the development of green products, is captured in the driver "access an international market for green products with traceability", which reflects the opportunity for Chile to participate in an emerging market. This driver is connected to "economic diversification through green industries", which describes the opportunity for Chile to create new markets based around sustainability attributes, such as energy renewable.

Finally, a further driver that is recognized as important is the "low cost of energy" - perceived as an important element in the medium term.



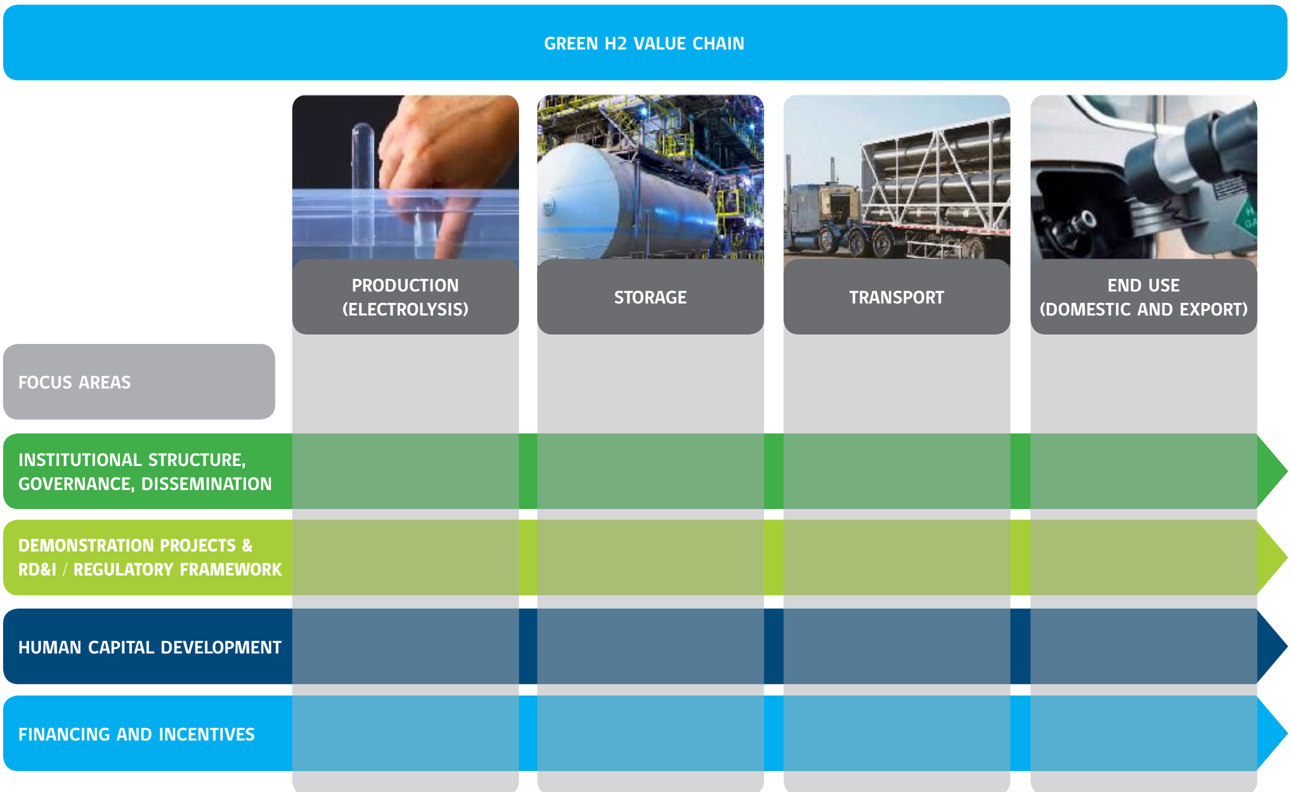


3. During the participatory process, the following **national vision** was consolidated

"To be global leaders in the production, use and export of green hydrogen and its derivatives, through technological development, the enablement of a competitive market and harnessing the recognized renewable energy potential of the country, in order to contribute to the realisation of a sustainable society."

4. **Value chain** and focuses for action

In order to achieve this vision, it is necessary to target action towards different cross-cutting focuses in the links in the green hydrogen value chain, including the stages of production, storage, transport and end use, and considering both the domestic consumption of hydrogen, as well as its export.



STRATEGIC FOCUSES

INSTITUTIONAL FRAMEWORK, GOVERNANCE & DISSEMINATION

Coordinate new projects and share knowledge to develop the market.

DEMONSTRATION & RD&I PROJECTS/ REGULATORY FRAMEWORK

Put green hydrogen into practice, through development and demonstration of regulatory framework.

HUMAN CAPITAL DEVELOPMENT

Prepare technicians and professionals to work in the green H2 market.

FINANCING & INCENTIVES

Generate enabling conditions for the development of the market.

According to the drivers and gaps identified in the diagnosis and the solutions proposed during the participatory process, four strategic focuses / pillars can be identified with cross-cutting actions:

- **Institutional framework, governance and dissemination:** Coordination of new projects and knowledge sharing to develop the market.
- **Demonstration and RD&I projects / regulatory framework:** Undertake industrial-scale green hydrogen demonstration projects and research, accompanied by the development of the specific regulatory framework.
- **Human capital development:** Preparation of technicians and professionals to work in the green H2 market.
- **Financing and incentives:** Generation of enabling conditions for market development through a range of sources of financing and incentive mechanisms.

The activities or actions defined for each strategic focus are defined below:

FOCUS 1. INSTITUTIONAL FRAMEWORK, GOVERNANCE AND DISSEMINATION

CHALLENGE

Extract from the VISION:

"To be global leaders... harnessing the recognized renewable energy potential of the country".

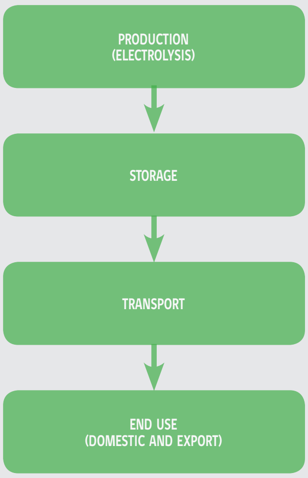
GAPS

Cross-cutting gaps (throughout the value chain):

"Lack of information to facilitate wider understanding of the potential of hydrogen as an energy carrier" among society and decision makers in the public and private sectors (including banking).

Gaps identified during the participatory process:

- Lack of coordination in the value chain.
- Lack of institutional structures to strengthen collaboration between public-private-academia.
- Lack of communication around the benefits and potential of green hydrogen as an energy carrier.



QUICK WINS

- Take advantage of the visibility of COP25, to show Chile's green hydrogen potential.
- Continue with annual International Seminars on green H2, bringing together companies with real experience.

ACTIONS

- Strengthen the public-private collaboration environment, and create links with academia.
- Dissemination and social awareness, through information and communication activities regarding green hydrogen. Delivery of seminars and workshops to share information regarding technology solutions and uses based on green hydrogen.
- Create institutions to lead the development of green hydrogen.

FOCUS 2. DEMONSTRATION AND RD&I PROJECTS / REGULATORY FRAMEWORK

CHALLENGE

Extract from the VISION:

"To be global leaders in the production, use and export ... competitive market..."

GAPS

PRODUCTION (ELECTROLYSIS)

- Production of green H2 not yet economically competitive with conventional H2 production.
- Lack of industrial scale pilots producing green H2 in Chile to demonstrate technical and economic feasibility.
- On-grid green hydrogen production: emission factor of the electricity network defines the "green" character of production (depending on an electricity mix that is not 100% renewable).

STORAGE

- Lack of technical economic and commercial analysis of storage options at national level.
- Lack of industrial-scale storage pilot projects of storage for use in electrical systems.

TRANSPORT

- H2 transport costs tend to be greater than natural gas transport costs.
- Intercontinental H2 transport ships are still in development.
- Transportation of H2 in the form of ammonia, methanol or other, requires transformation processes at the ports of origin and destination; costs increase in correlation with distances.

END USE (DOMESTIC AND EXPORT)

- Available technologies for mining trucks in R&D development.
- Specific safety regulations and standards are required.
- Lack of specific regulatory framework (tax) to support green hydrogen in transport.
- Supply logistics not yet available.
- Maximum injection percentages allowed into natural gas networks not yet defined.

ACTIONS

Demonstration projects and RD&I:

- R&D Technology Program for Dual fuels and fuel cells.
- R&D Technology Program for solar fuels for industry.
- Hydrogen R&D strand at the Chilean Institute for Clean Technologies.
- R&D project for high temperature hydrogen production.
- Industrial project to replace chemical imports.
- Demonstration project for hydrogen buses.
- Project for the injection of hydrogen into natural gas network.
- Green hydrogen production and export project.
- Green hydrogen production and logistics supply chain for industry and mining project.

Regulatory framework:

- Climate change policy and regulations.
- Technical and safety standards (Technical Committee).
- CO2 tax.

FOCUS 3. HUMAN CAPITAL DEVELOPMENT

CHALLENGE

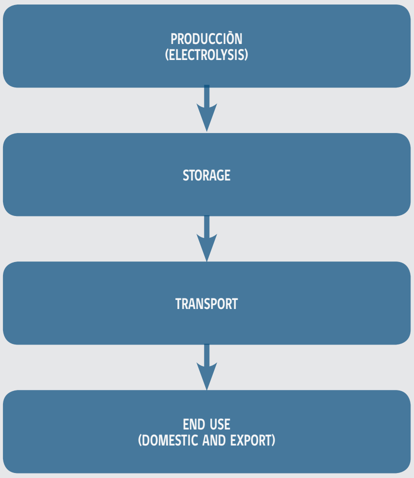
Extract from the VISION:

"...the enablement of a competitive market..."

GAPS

Cross-cutting gaps (throughout the value chain):

Lack of trained human capital (engineering, technicians, security, etc.)



ACTIONS

- Human capital training program.
- Development of courses on university degrees for professional training.
- Development of competency profiles for technicians, development of training modules, training and certification of competencies.

FOCUS 4. FINANCING AND INCENTIVES

CHALLENGE

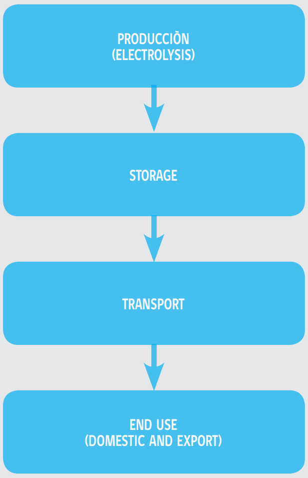
Extract from the VISION:

"To be global leaders in the production, use and export... the enablement of a competitive market..."

GAPS

Cross-cutting gaps:

- Lack of financing models for industrial-scale demonstration and RD&I projects.
- Lack of specific regulatory framework (tax) for green hydrogen in transport.
- Lack of mechanisms / instruments for green H2 certification.



QUICK WINS

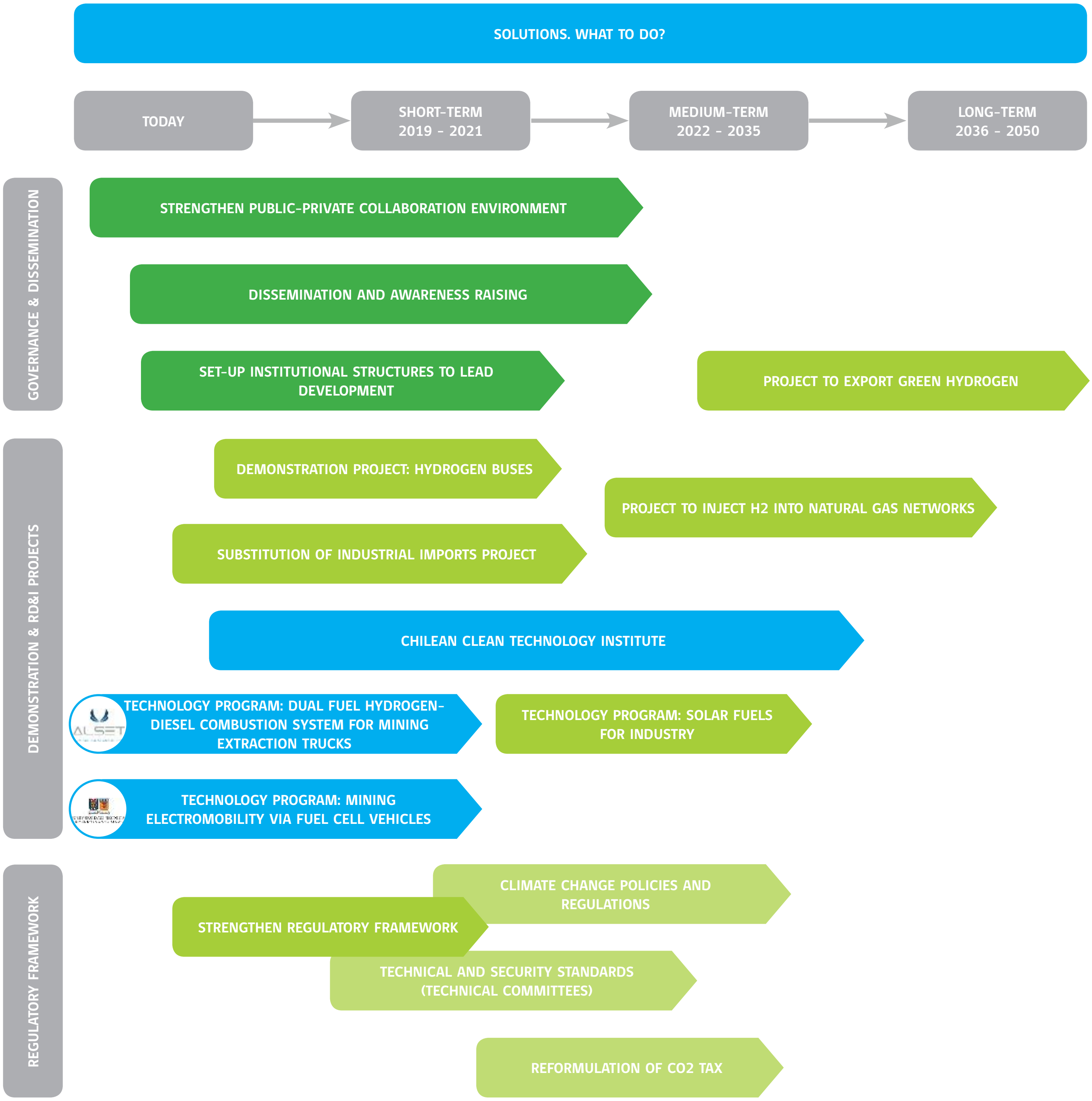
- Take advantage of the financing instruments of CORFO (Chilean Economic Development Agency) and the Institute for Clean Technologies in the next available funding opportunity, for the investment and development of demonstration projects.
- Take advantage of COP 25 to attract foreign companies to carry out projects in collaboration with local partners in Chile.

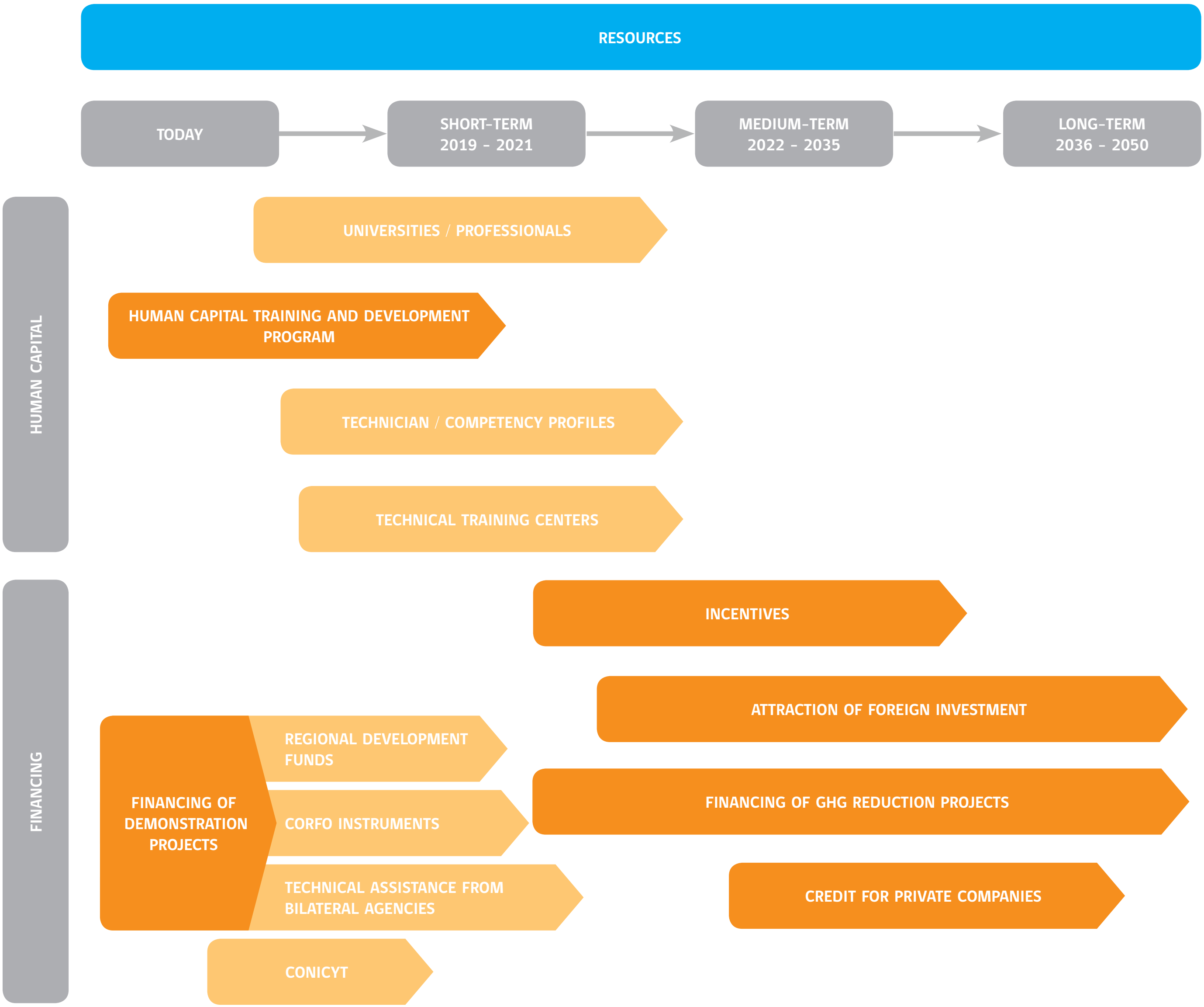
ACTIONS

- Financing of demonstration projects:
  - Coordinate with regional development funds.
  - Apply to Corfo financing instruments.
  - Apply for technical assistance from bilateral agencies.
  - Apply to ex-Conicyt funding streams.
- Incentives provided by national and multilateral organizations.
- Attraction of foreign investment.
- Apply to financing for GHG reduction projects.
- Credit for private companies.

PROPOSED ROADMAP

Based on the themes that emerged during the participatory process and the preliminary strategy proposal for the development of the green hydrogen market in Chile, the following Roadmap is proposed, with initiatives in the short, medium and long term:




RESOURCES
TODAY
SHORT-TERM 2019 - 2021
MEDIUM-TERM 2022 - 2035
LONG-TERM 2036 - 2050
HUMAN CAPITAL
UNIVERSITIES / PROFESSIONALS
HUMAN CAPITAL TRAINING AND DEVELOPMENT PROGRAM
TECHNICIAN / COMPETENCY PROFILES
TECHNICAL TRAINING CENTERS
FINANCING
INCENTIVES
ATTRACTION OF FOREIGN INVESTMENT
FINANCING OF DEMONSTRATION PROJECTS
REGIONAL DEVELOPMENT FUNDS
CORFO INSTRUMENTS
TECHNICAL ASSISTANCE FROM BILATERAL AGENCIES
FINANCING OF GHG REDUCTION PROJECTS
CREDIT FOR PRIVATE COMPANIES
CONICYT

5. Conclusions

The shared vision defined by the stakeholders that participated in the workshop process incorporates four strategic areas of action along the value chain (production, storage, transport, and end use).

The first focus is related to institutional structures, governance and dissemination, where the objective is to mobilize and coordinate new projects and disseminate knowledge to promote the development of the green hydrogen market. To achieve this, the strategy focuses on initiatives that allow Chile to build its reputation as a relevant player in the green hydrogen industry. This includes the coordination of public and private sector actors and mobilization of projects, in addition to encouraging instances of collaboration and knowledge transfer at national and international level.

The second focus corresponds to demonstration projects, RD&I and the supporting regulatory framework, where through concrete initiatives, technical operating and performance parameters and performance levels can be obtained, which will reduce the perception of risk as the market grows. To achieve this, the initiatives focus on identifying industrial scale demonstration and RD&I projects, in different market niches, geographic macrozones and for different final uses. This goes hand in hand with pushing forward the development of the required regulatory framework.

The third focus relates to human capital, since this is required to serve the national green H2 industry and enable a competitive market. Relevant activities linked to the strengthening of human capital include the training of professionals and technicians on green hydrogen themes in Chile.

The fourth focus is around financing and incentives. This seeks to accelerate investment in and the development of industrial scale demonstration projects, in order to boost the market in terms of production and uses, and progress towards the export of green hydrogen. This requires initiatives that enable the emergence of regulatory conditions and incentives for market development.

For the success of the Strategy, the mobilization and active participation of different stakeholders is required. One of the advantages found in this study, is that Quick Win opportunities have been identified, which may strengthen the visibility of market development opportunities in Chile. This includes international seminars, COP25 in Chile or the support of CORFO and the Institute of Clean Technologies that is in development.

Green hydrogen

National strategy proposal to stimulate the market in Chile

Green H2

COMITÉ SOLAR E INNOVACIÓN ENERGÉTICA | CORFO | Ministerio de Energía, Gobierno de Chile | Chile en marcha