Opportunities for the development of a solar hydrogen industry in the regions of Antofagasta and Atacama:

Innovations for 100% renewable energy system

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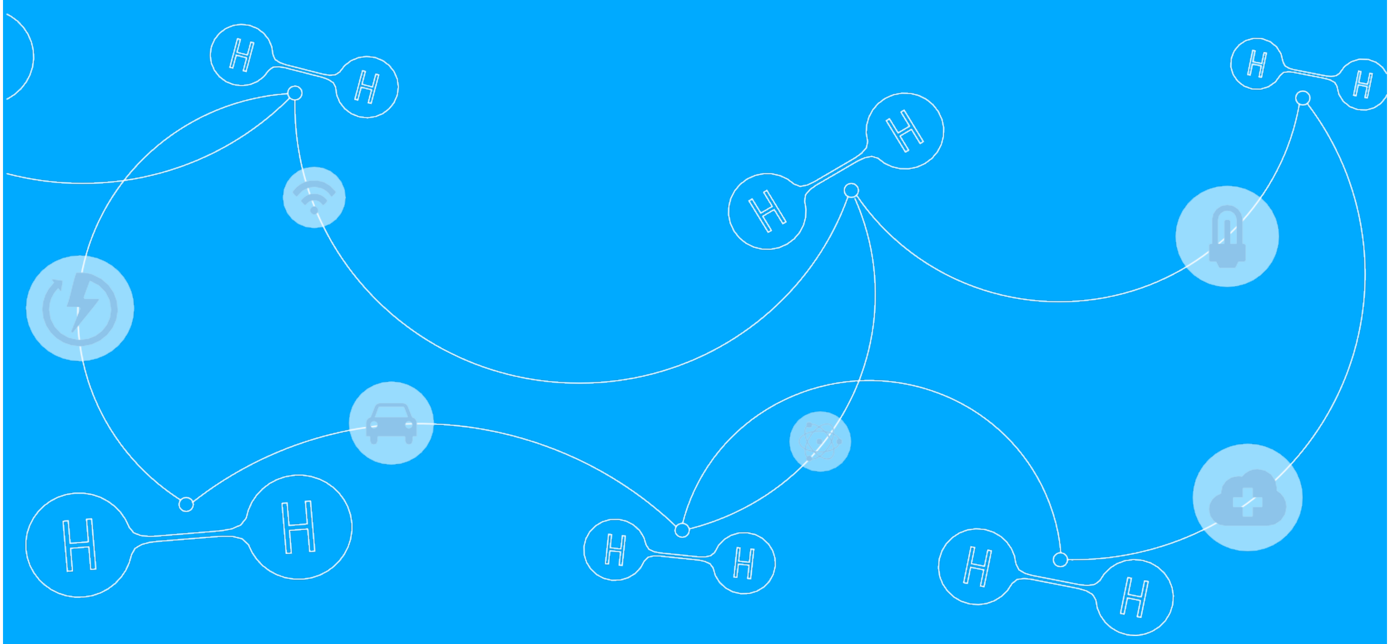

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EXECUTIVE SUMMARY

Introduction

Motivation

At the COP21 ("Conference of the Parties") held in Paris in 2015, 195 countries, including Chile, met to sign a legally binding agreement to maintain global warming "*well below two degrees Celsius relative to pre-industrial levels, and to pursue efforts to limit the increase in temperature beyond 1.5 degrees Celsius*" within this century. This goal is ambitious, since it will require the world to limit accumulated carbon dioxide emissions related to energy to less than 900 Gton by the year 2100, an amount that will be exceeded by 2050 if it continues the current path.

According to the most updated study of the Chilean "*Sistema Nacional de Inventarios de Gases de Efecto Invernadero"*, the Energy sector (which includes the use of fuels in stationary or mobile applications) covered about 70% of total national GHG emissions by 2013, equivalent to 75,000 Kton of CO_2. The region of Antofagasta and Atacama contributed 19.8% and 8.3% respectively, both being within the 5 regions that emit the most at the country level. In Antofagasta, emissions associated with the use of fossil fuels for electricity generation and mining corresponded to 70% and 7.4% respectively. In Atacama, same values corresponded to 59% and 20.5%[1].

In recent years, hydrogen, produced through renewable energy, has emerged as a promising energy vector to decarbonize the energy, industrial and transport sectors, improve energy security conditions, mitigate greenhouse gases and open up new markets.

In this context, the Solar Committee, belonging to the Corporation for the Promotion of Production (CORFO), poses the challenge of deepening the opportunities that solar energy offers in northern Chile to achieve a 100% renewable region.

Scope and Objectives

The purpose of this study is to develop a 100 % renewable energy vision for the regions of Antofagasta and Atacama. During the development of this vision, current and future business opportunities related to the development of solar energy and the production of hydrogen were identified. The special focus given to solar energy is based mainly on the excellent solar resource present in these regions, which have the best irradiation levels in the world.

The specific objectives of the study are:

- Establish a short and long-term vision to achieve a 100 % renewable energy matrix in the regions of Antofagasta and Atacama;
- Evaluate the performance of a 100 % renewable matrix in the regions of Antofagasta and Atacama;
- Design the energy transition of the regions of Antofagasta and Atacama oriented to a 100 % renewable matrix, considering the inclusion of specific indicators to measure their progress;
- Raise relevant information related to the production of hydrogen from renewable energies, including the most relevant actors worldwide;

[1] From the national report of GHG emissions inventory, series 1990 – 2013, published the 12th of May 2017.

- Identify opportunities for the development of an economy based on 100 % renewable energies, prioritizing solutions based on the use of hydrogen as an energy vector.

Methodology

The study is divided into two sections:

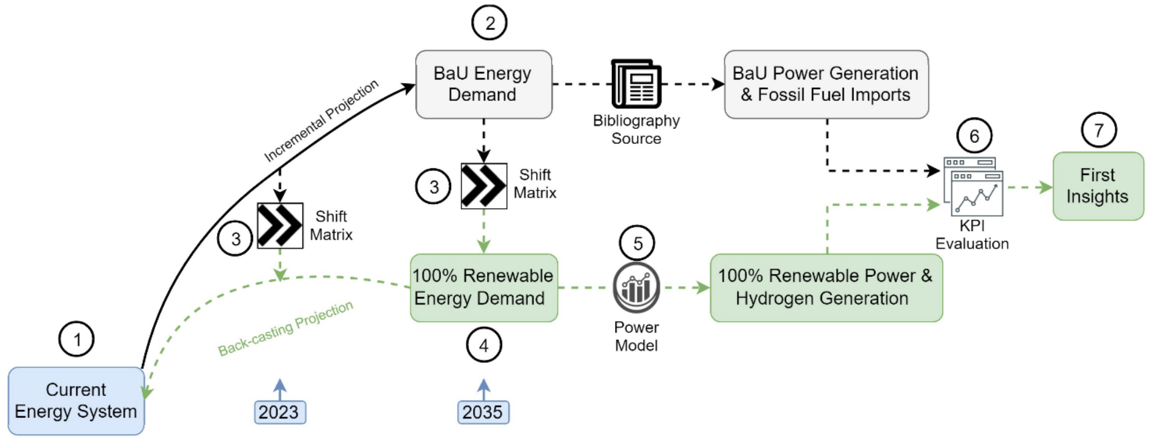
- Development of a 100 % renewable energy vision;
- Hydrogen economy and business Case screening.

Both the renewable vision and the identified business cases were formulated for a short-term and long-term scenario defined at 2023 and 2035 respectively.

100 % Renewable Energy Vision

The 100 % renewable energy vision consists on decarbonizing the entire energy demand, e.g. electricity and fuel related to all the four energy sectors; Mining, Industry, Transport, and Commercial-Public-Residential (CPR). In order to do so, the following methodology was followed:

1. **Analysis of the current energy system**, in terms of energy demand by sector and energy source, and in terms of existing energy generation;
2. **Incremental Projection of the energy demand**, by sector and energy source until 2035 according to a Business as Usual approach.
3. **Identification of optimization levers and creation of a shift matrix;**
    a. Identification of energy efficiency actions**,**
    b. Substitution of fossil fuels by renewable electricity, renewable hydrogen and solar thermal, depending on the application. A distinction is made between the technologies available in 2023 and 2035.
4. **Calculation of the Energy Demand**, per energy source/vector for 2023/2035 for the 100% Renewable Energy Vision
5. **Running the Long-Term Capacity Expansion Planning model**, considering the 100 % renewable energy target in 2035. The model returns the mix of electricity-producing and hydrogen-producing assets in both years, as well as their resulting energy production. The electricity-production for the BaU comes from local projections.
6. **Comparison Analysis,** of both scenarios is done according to a set of Key Performance Indicators (KPIs), according to four categories: production KPIs, demand KPIs, cost KPIs, and environment KPIs.
7. **First Insights** towards a 100% Renewable Energy System in 2035.



Methodology for the development of the 100% Renewable Vision.

The 100 % renewable energy vision takes a disruptive approach, in which from 2016 onwards[2], only system-level cost-optimal renewable investments are made. Abstraction is made of potentially existing barriers that make such system-based optimal decisions infeasible or uncompetitive, i.e. non-perfect competition and regulatory barriers. As a result, the investment decision for the 100 % renewable energy vision might be substantially different from the currently planned investments for the near-term future.

The development of the mid/long-term 100 % renewable energy vision exercise is based on a back-casting approach. For this approach, the desired condition at the end-game is defined, i.e. a 100 % renewable energy provision for the northern regions, and steps are identified to attain this condition in the most effective manner[3].

A long-term capacity expansion model is run for the 100 % renewable energy vision, with a nodal representation of the both northern regions and the rest of Chile. The transmission capacity within the regions was made abstraction off, thereby simplifying the model. The transmission capacity between the regions is modelled, so that the interregional constraints are respected. Furthermore, the capacity expansion plan includes the investments in electrolysis that are required to produce hydrogen.

The outcome of the back-casting approach is the evolution of the energy supply assets for the 100 % renewable energy vision, in 2023 and 2035. This outcome is then compared to the Business as Usual (BAU) model, which is based upon an official scenario provided by the Ministry of Energy. The PELP study (Proyección Energética de Largo Plazo 2017-2018) formulated 5 scenarios, characterized by the following parameters; social impact, energy demand, energy storage with batteries, environmental externality costs, investment cost of renewable asset and fossil fuel prices, which have a certain qualitative value (Eg. Low energy demand, high environmental externalities costs or low renewable assets costs). Each scenario is defined by a different combination of those characters

Scenario C was chosen as the referential one to be used as a Business as Usual. This scenario assumes referential energy demand growth, average cost of renewable assets, actual taxes on CO_2 emissions and referential or medium fossil fuel costs.

[2] This study considers the year 2016, because at the moment of its realization all the annual energy databases were complete for that year.
[3] This is in contrast with an incremental approach, where one let the system evolve from the current situation according to a set of scenarios, which are then evaluated and compared.

The comparison of both scenarios (100 % RES and BAU) is done according to a set of Key Performance Indicators (KPIs), according to four categories; Production KPIs, Demand KPIs, Cost KPIs and Environmental KPIs. These are used to quantify in a non-exhaustive measure the evolution of the transition towards a 100 % renewable energy system in Antofagasta and Atacama. These will be used to define a framework for the roadmap towards a 100 % renewable energy system in 2035.

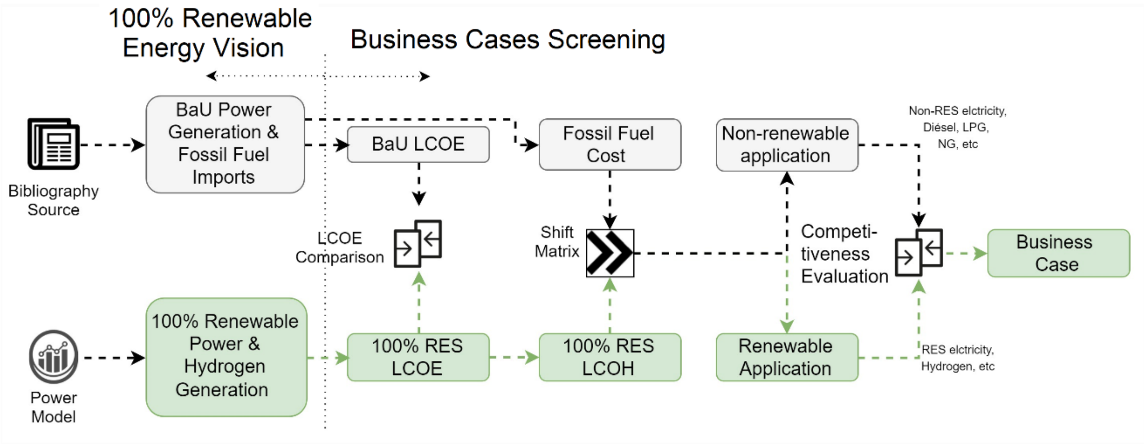
Hydrogen Economy & Business Cases Screening

This section aims at screening the business cases that could boost the transition of the northern regions towards the concretization of the 100% Renewable Energy vision[4]. The methodology is as follows:

1. **The hydrogen economy overview** gives the necessary background to understand the global and local status of the hydrogen economy;

- **Energy supply chain modeling** for renewable electricity and hydrogen supply. The shift from non-renewable energy to renewable electricity and renewable hydrogen, as defined in section one, are assessed by calculating the levelized cost of electricity (LCOE) and hydrogen (LCOH).

2. **Business opportunities** are evaluated by comparing the cost of the renewable energy applications with the cost of the non-renewable alternatives.



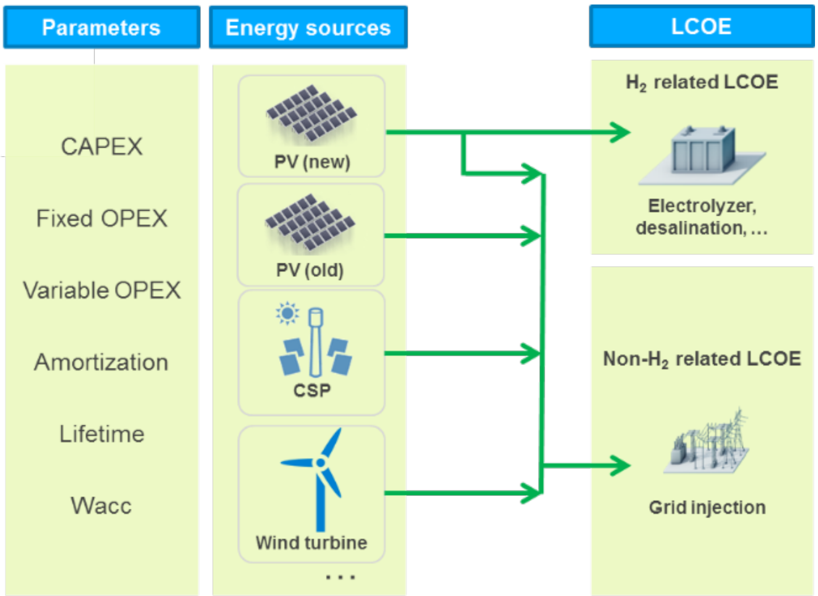
Methodology for the business cases screening.

The **Levelized Cost of Electricity** (LCOE) is used as a general metric to measure the projected life-cycle costs of electricity across the different scenarios. Such representation allows to compare different set of technologies (e.g. PV, CSP, wind, and coal) with different lifetimes, CAPEX/OPEX values, capacity factors, etc for different scenarios with a simple metric: $/MWh[5].

[4] Due to the fact that Hydrogen is needed for the decarbonization of non-electrical energy vectors, and that the concept of the Hydrogen Economy in the local context is still immature, this chapter starts with an introduction to the global and local hydrogen market in order to increase the reader understanding

[5] Where $ corresponds to American dollars.

As the LCOE is an important parameter in the **Levelized Cost of Hydrogen** (LCOH), the allocation of the different electricity generation assets for hydrogen related and non-hydrogen related production is critical. Therefore, a range of LCOE values is calculated to arbitrate between hydrogen related and non-hydrogen related applications. This range of LCOE values, depending on the electricity cost assigned to hydrogen production, results in a range of LCOH values.



Representative scheme of LCOEs, Hydrogen is produced by Solar PV.

The hydrogen value chain is modeled with a focus on the production (upstream LCOH), from the desalination unit to the outlet of the electrolyser. Compression, storage, and distribution steps are not included in the analysis, because they are “case sensitive” to the final application. A deeper analysis is required to investigate the required storage capacity, the adequate pressure levels, as well as the optimal distribution infrastructure. These steps are therefore not reflected in the LCOH.

Based upon the shift matrix defined in WP1, business cases were assessed. For each application evaluated in the shift matrix, the substitution is quantified, e.g. from non-RES electricity to RES electricity, from fossil fuel to hydrogen, etc.

The upstream LCOE and LCOH values are used to assess the competitiveness for each business case (e.g. fuel cells for heavy-duty transport, hydrogen for ammonia production…), by comparing to the traditional alternative. For the applications where the renewable option has a positive margin on the operational (mainly fuel) costs, the business case is considered as promising. A margin on the operational costs does not necessarily mean that the application is competitive, as the renewable alternative might have higher capital costs. Nevertheless, the OPEX margin gives a clear idea on the potential competitiveness, as many of the renewable technologies are expected to become less expensive over time.

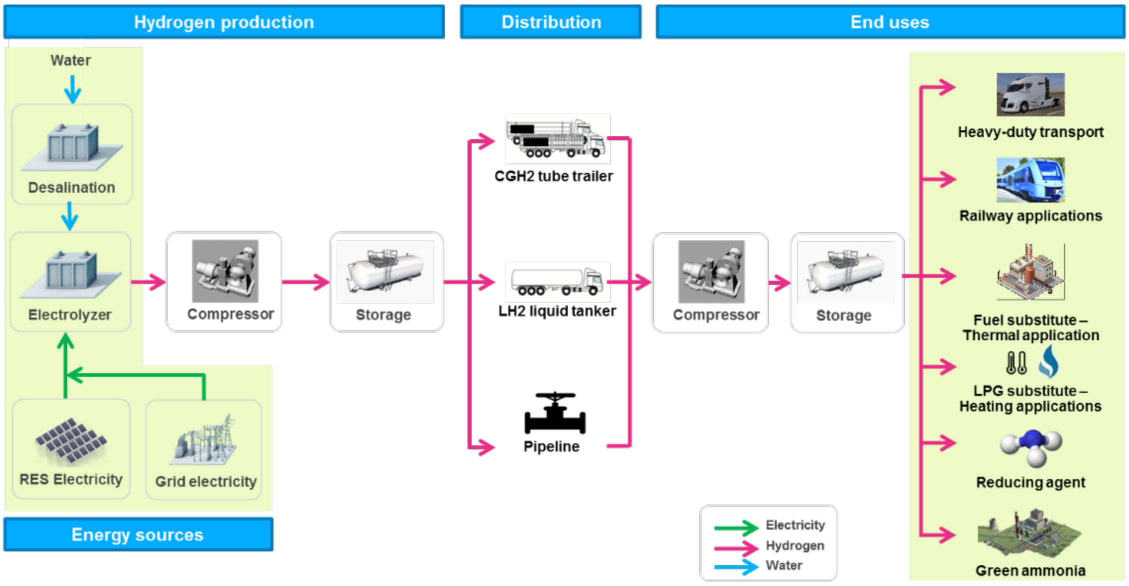


Diagram of the Hydrogen value chain.

Results and Discussion

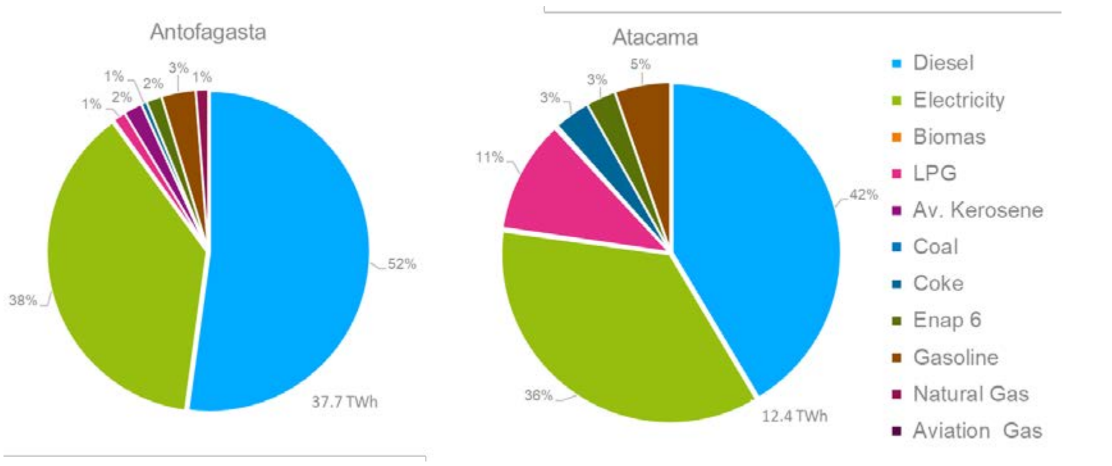
Baseline: Actual Situation & The BAU Scenario

Actual Situation

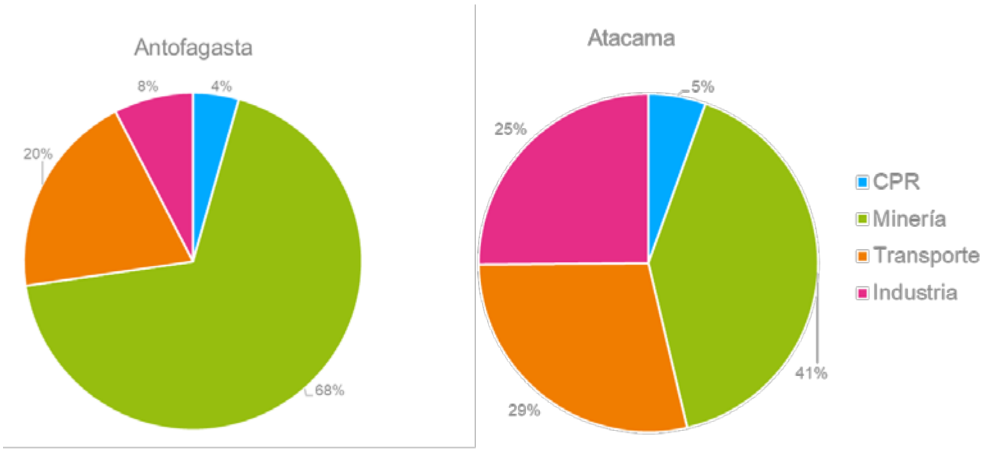
For both Antofagasta and Atacama, the status of the energy system is analyzed for 2016. In Antofagasta, more than 85 % of the energy is consumed by mining and transportation. The mining sector alone accounts for more than 85 % of the electricity consumption, as the transport sector mainly uses fossil fuels. In Atacama, the mining and transport sector consume 70 % of all energy, and there is a 25 % share of energy consumption due to industry. Mining and industry account for more than 90 % of the electricity consumption.

In 2016 the mining sector total energy demand for Antofagasta accounted for 25.8 TWh, of which 48 % corresponds to electricity, 48 % to Diesel, and 4 % to other fossil fuels. For Atacama the mining sector total energy demand accounted for 5.05 TWh, of which 57 % corresponds to Electricity, 36 % to Diesel, and 7 % to other fossil fuels.

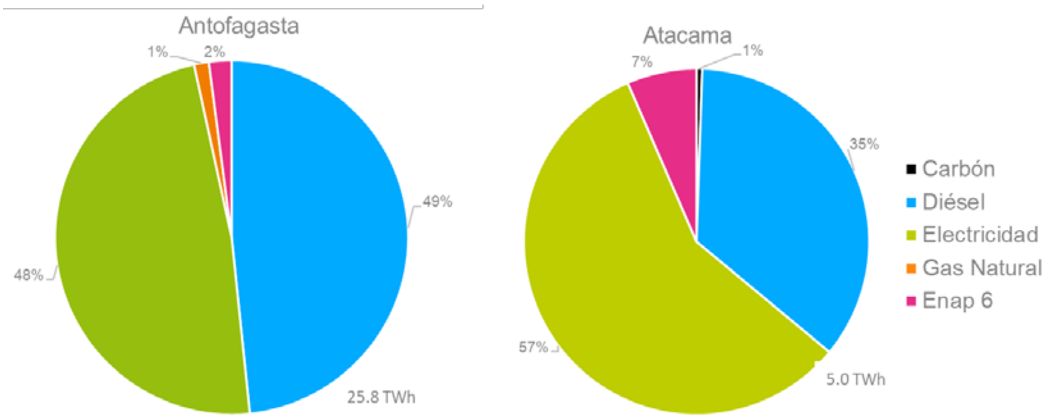
Putting these numbers in perspective, this mean that the mining sector requires an approximated installed capacity of 1.7 GW for electricity demand. Similarly, the diesel demand is equivalent to importing a total of 35,265,000 barrels/year of crude, equivalent to approximately 50 % of ENAP’s refining capacity (Aconcagua and Bio-Bio together).



Energy demand per type for Antofagasta and Atacama in 2016.



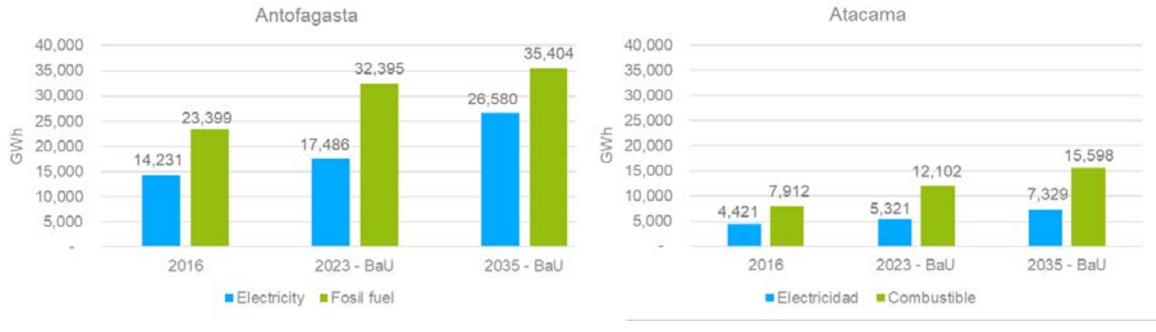
Energy demand by sector for Antofagasta and Atacama in 2016.



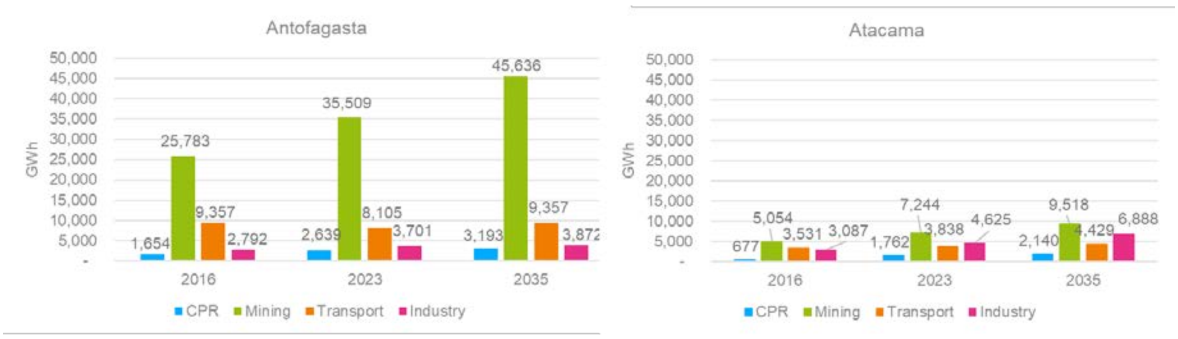
Energy demand for the mining sector for Antofagasta and Atacama in 2016.

Business as Usual Scenario

The projected energy demand for the BAU Scenario, for both 2023 and 2035, is summarized in the following figures.

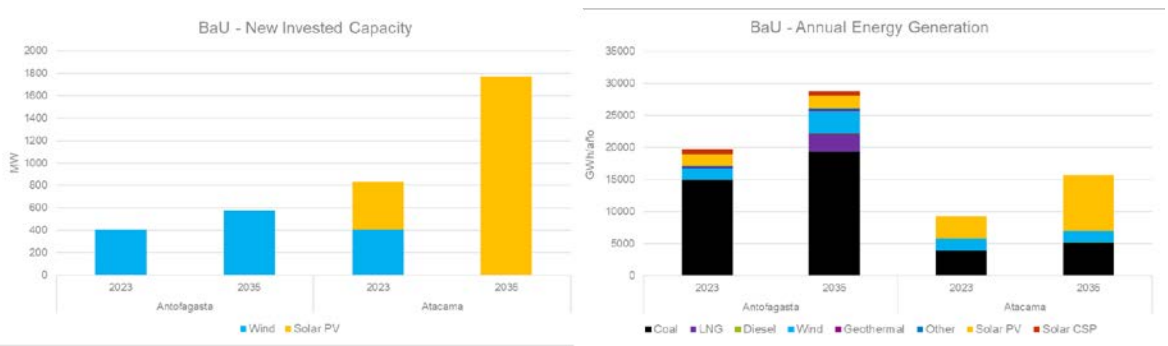


Energy demand for the BaU scenario per type for Antofagasta and Atacama Region in 2016.



Energy demand for the BaU scenario per sector for Antofagasta and Atacama Region in 2016.

The Power Generation for the BAU scenario is summarized in the following figures.



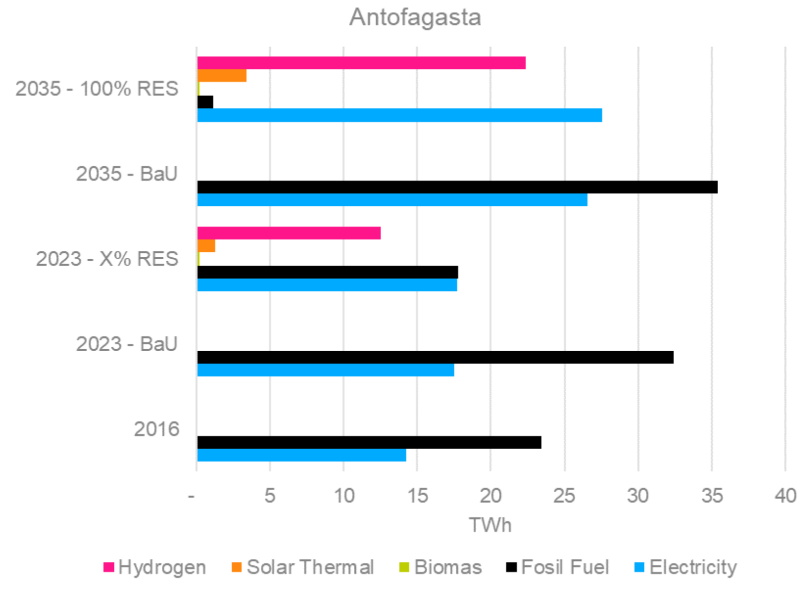
New invested capacity and energy generation for the BaU scenario for Antofagasta and Atacama.

The End Game – Towards a 100% Renewable Energy System

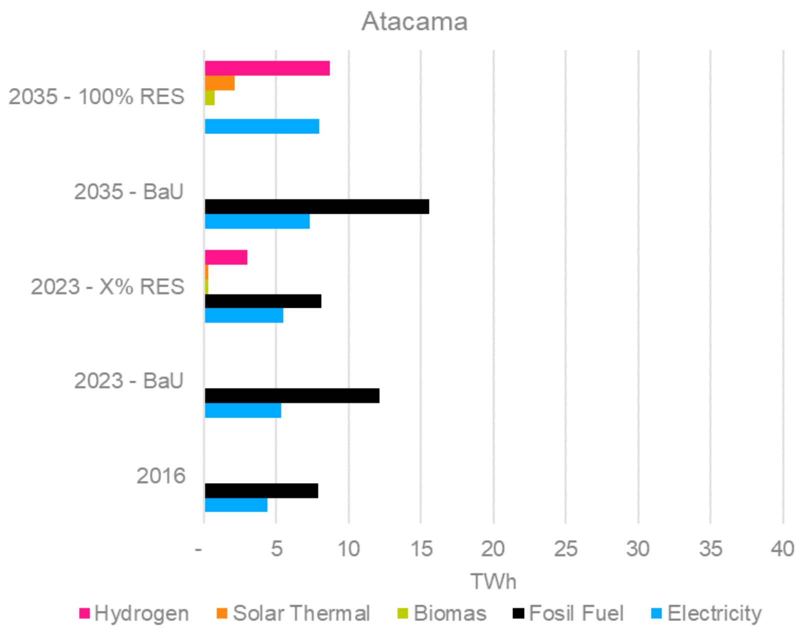
For the **renewable energy vision in 2023**, only a fraction of the fuels can be substituted by renewable electricity and hydrogen, accounting for 20-25 % of the total energy demand of the northern regions. This is due to the partial substitution of diesel-fueled combustion engines by hydrogen-fueled alternatives, a complete substitution is not considered by 2023. Nevertheless, this is already **a substantial potential for hydrogen in the short term**, which can be realized by retrofitting internal combustion diesel engines for using a diesel-hydrogen blend, or by substituting a fraction of diesel combustion engines with fuel cells electric propulsion.

For the **100 % renewable energy vision in 2035**, fossil fuels can be substituted by renewable hydrogen, renewable electricity, and solar thermal process heat, for all applications except marine and aviation. Also, all electricity production can be renewable by 2035. As a result, electricity and hydrogen will be the dominating energy vectors in 2035 for the renewable energy vision, with **hydrogen supplying more than 40 % of the energy needs** of Antofagasta and Atacama. A small but noticeable fraction of solar thermal process heat is be present as well, for thermal processes in the mining and industrial sector.

A comparison of the expected total final energy demand for the different years and the both scenarios is illustrated in the following figures.



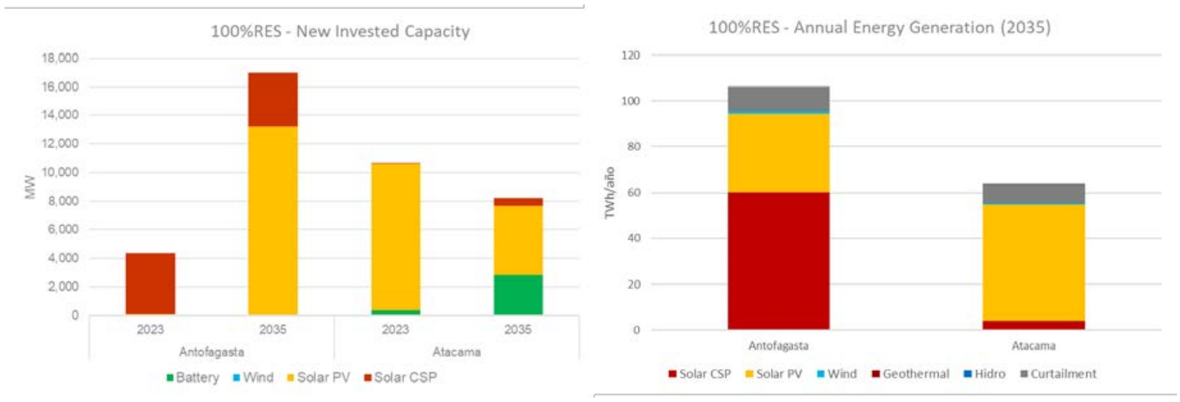
Comparison of the projected energy demand for 2023 and 2035 in Antofagasta for both scenarios.



Comparison of the projected energy demand for 2023 and 2035 in Atacama for both scenarios.

The power generation is **dominated by PV and CSP** for the 100 % renewable energy vision in 2035. PV provides the lowest-cost electricity if it can be consumed instantaneously, while CSP provides the lowest-cost dispatchable electricity, thanks to the multi-hour thermal storage capabilities. In Antofagasta, CSP will provide around 70 % of the electricity production, and PV will account for around 30 % of power production. In Atacama, PV will provide more than 90 % of the power production, and CSP accounts for less than 10 %. Furthermore, around 10 % of the produced power production of Atacama is passing through battery energy storage.

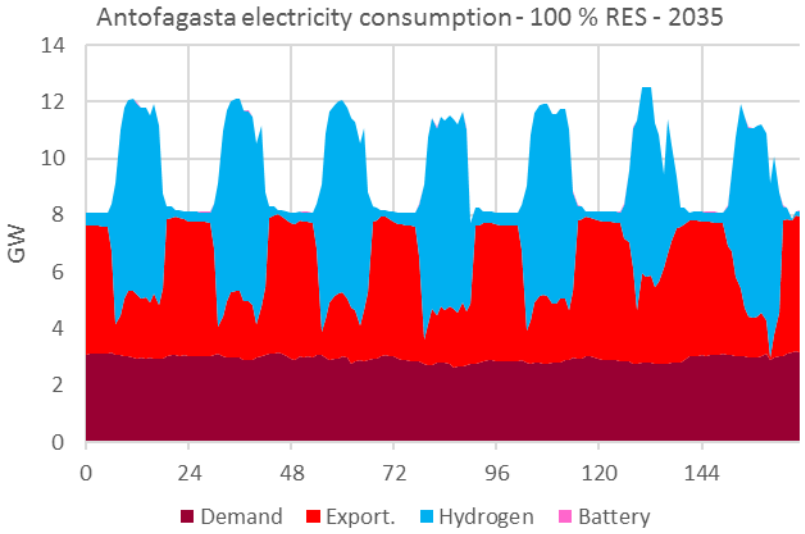
Renewable energy curtailment is part of the cost-optimal solution for the 100 % renewable energy vision. **More than 12.5 %** of the renewable energy would be curtailed in 2035, because the solar assets are sized at supplying sufficient renewable energy in winter, when there is less solar irradiation than in summer. Therefore, there would be a **surplus of renewable energy in summer**, which is too expensive to store.



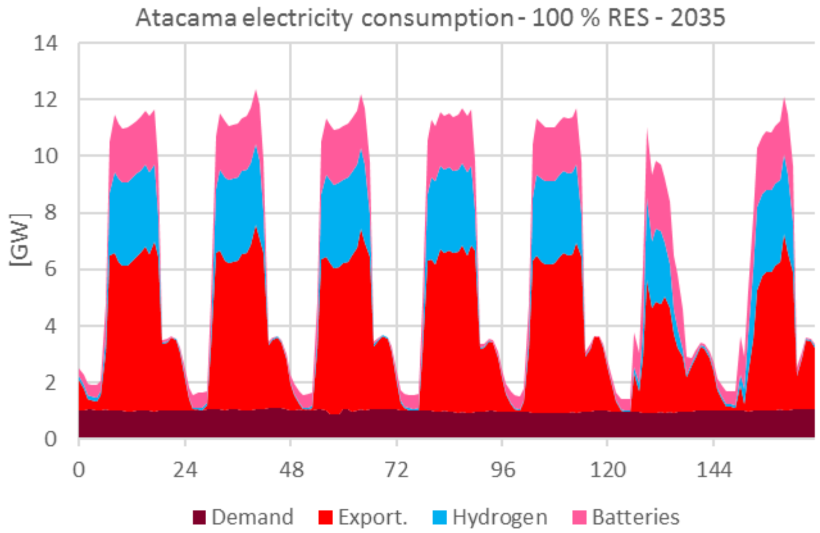
New invested capacity and energy generation for the 100%RES scenario for Antofagasta and Atacama.

The **hydrogen production would be synchronized with the PV power output** in both regions. This illustrates that it is more cost-effective to oversize the electrolysis assets to run on PV power, instead of sizing them for baseload and running on a combination of PV and CSP power. Obviously, this implies the presence of a hydrogen storage infrastructure that allows to match the production and demand profiles of hydrogen. This match of PV and hydrogen production shows that the development of the hydrogen supply infrastructure is relatively independent of the renewable electricity supply infrastructure. The figures below show the hourly electricity consumption during a summer week in Antofagasta and Atacama for the RES scenario in 2035.

There would be a **substantial export of electricity to the rest of Chile** for both Antofagasta and Atacama. About 40 % of the renewable energy produced in Antofagasta and Atacama could be exported to the rest of Chile. For Antofagasta, most of the power exported is supplied by CSP, while for Atacama, the power export is synchronized with the PV power output. This results in a **complementary power export profile towards the rest of Chile**, effectively supplying renewable power during the entire day.



Electricity hourly demand for a typical summer week in Antofagasta for the 100%RES scenario in 2035.



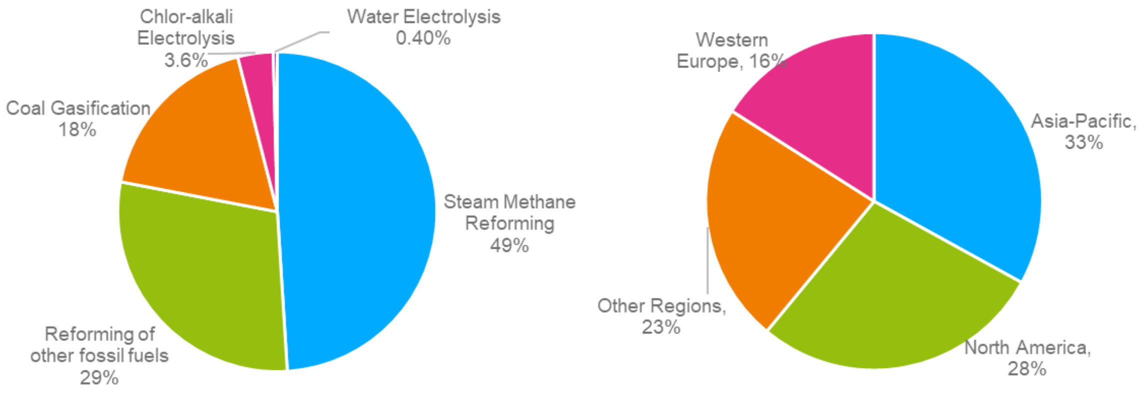
Electricity hourly demand for a typical summer week in Atacama for the 100%RES scenario in 2035.

Hydrogen Economy: Global and Local Context

Global Context

Globally, there is an annual production of 60,000 kton hydrogen, of which more than 95 % is produced from fossil fuels, i.e. natural gas, liquid fossil fuels, and coal. Furthermore, more than 3.5 % of the global hydrogen production is as a by-product from Sodium Chloride Electrolysis. Less than 1 % of the global hydrogen production is from water electrolysis.

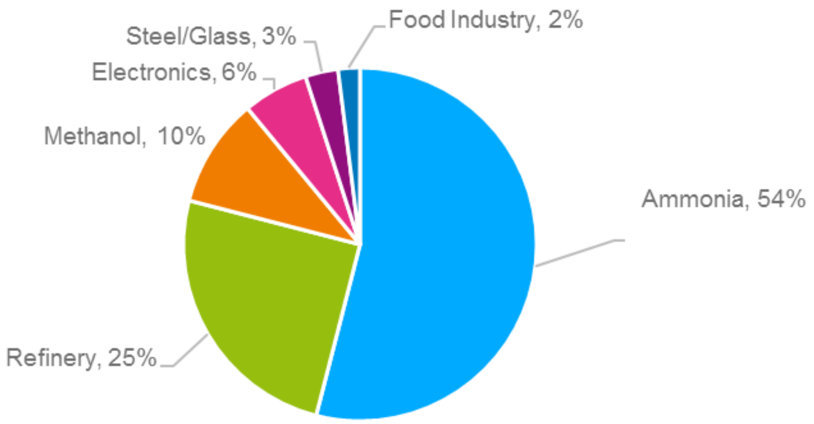
The global hydrogen production is dominated by Asia-Pacific, North America, and Western Europe. These three regions are responsible for more than 75 % of the global hydrogen production.



Left.: Global production of Hydrogen by source. Right: Global production of Hydrogen by region.

Most of hydrogen is used by the chemical and process industry, in a few specific sectors. Today, more than 50 % of the hydrogen globally produced is used by the ammonia industry. Approximately 25 % of the global hydrogen production is used by refineries, and 10 % for methanol production. The other sectors having a noticeable global hydrogen demand today are the electronics industry, steel/glasswork production, and the food industry.

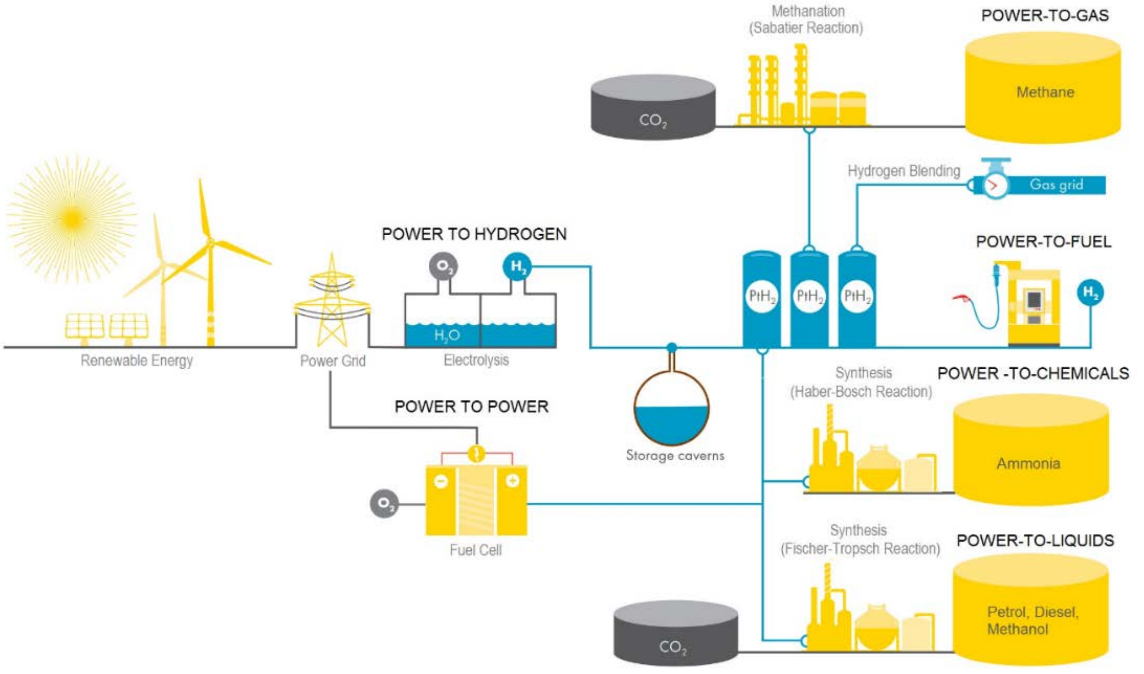
The current hydrogen production is dominated by a limited set of large global players, matching the supply mode with the needs of the clients.



Main global uses of Hydrogen.

The hydrogen market of tomorrow, driven by a global Energy Transition that aims at decarbonizing the whole energy system, will have a much higher share due to the inherent capacity of using Hydrogen to couple different sectors.

Hydrogen can be obtained by electrolysis from electricity produced with renewable electricity. If there is a corresponding energy demand, the hydrogen can fulfil it directly. However, it can also be stored in bulk tanks as pressurized gas and retrieved when supplies are low. Even more, hydrogen can be converted into other energy carriers. Converting renewable electricity via hydrogen into other energy carriers, the Power-to-X concept (PtX), can result into different utilization pathways as depicted in the following figure.



The role of green hydrogen as an energy vector (Power-to-X concept).

The PtX concept shows that the regions of the world with the cheapest LCOE might have the opportunity to produce the cheapest green chemicals of the world, untapping a new premium market.

Local Context

In Chile, the hydrogen situation is far from the global trend, for using it either as raw material for the chemical industry or energy vector. Chemicals such as ammonia, methanol, and hydrogen peroxide, produced mainly from methane gas, are imported through freighters in the main ports of the country, relegating a minority portion to local production.

Likewise, the use of hydrogen as a vector for decarbonization of the entire energy matrix of the country through use in systems "Power to Power, Power to Gas and / or Power to Chemical is unknown. There are no concrete industrial projects for its implementation, except for some research and development initiatives of universities and government entities;

- Two technological programs promoted by CORFO
  - Dual hydrogen-diesel combustion for heavy duty mining trucks.

- Fuel Cells for mining fleets, emphasis on underground mining.

- A Power-to-Power (batteries and hydrogen) pilot project by Electro Power System at the Cerro Pabellón geothermal plant.

Currently, the main use of hydrogen in Chile has been relegated to the background as a chemical agent for the industry with a marked participation in the oil refining, and to a lesser extent in the food industry, generator cooling, glass production, and heat treatment of metals.

Competitive Advantage

In Northern Chile, there is a unique opportunity to develop competitive green hydrogen production to meet local needs and, in the future, to export hydrogen to other regions. The comparative advantages of the Antofagasta region occur throughout the hydrogen value chain are summarized in the following table.

The establishment of a hydrogen economy in the regions of Antofagasta and Atacama could transform Chile into a major producer of green hydrogen, for local use and for export. The main current market for hydrogen corresponds to ammonia production required for fertilizers, which are now supplied by hydrogen from steam methane reforming. Through renewable hydrogen, Chile could once again become a main exporter of fertilizers and compete for a new premium market, i.e. low-emission fertilizers.

Production	Transport and Storage	Utilization
Highest solar generation potential in the world, with a horizontal global irradiation (GHI) greater than 2,800 kWh/m^2 and a direct normal irradiation (DNI) higher than 3,800 kWh/m^2.	Solar and water resource in the same place of potential consumption, e.g. Mining.	Large number of potential direct consumers concentrated in the same region, e.g. Mining, Industries, cities, ports, airports, trains, heavy transport, etc.
Good wind resource associated with certain high potential sites, e.g. Tal Tal, and existing geothermal resources.	Existing infrastructure of gas pipelines, i.e. Gas Atacama and Norandino.	Imminent need for energy storage for integration of solar and wind energy.
Existing Water Desalination plants due to mining activity	Existing power distribution and transmission infrastructure.	High demand for Ammonium Nitrate for explosives, which are manufactured from Ammonia.
Desert area with less impact on communities.	Existing water infrastructure, pumping from the coast to the mountains.	Interest of the mining sector to achieve a greener Mining (massive diesel consumption).
	Existing rail and port infrastructure.	

Comparative advantages of the Antofagasta Region for implementing a hydrogen economy.

The establishment of a hydrogen economy in the region of Antofagasta and Atacama, could transform Chile into a leading country in the use and export of green hydrogen. According to the latest report of the Hydrogen Council "Hydrogen Scalling Up", by 2050 hydrogen could cover up to **18% of the final energy demand**, could drop **6 Gton of CO2 annually** and could represent a market of **2.5 trillion dollars a year.**

Business Opportunities

Levelized Cost of Electricity

The projected levelized cost of electricity for both northern regions in the 100%RES scenario is summarized in the following table.

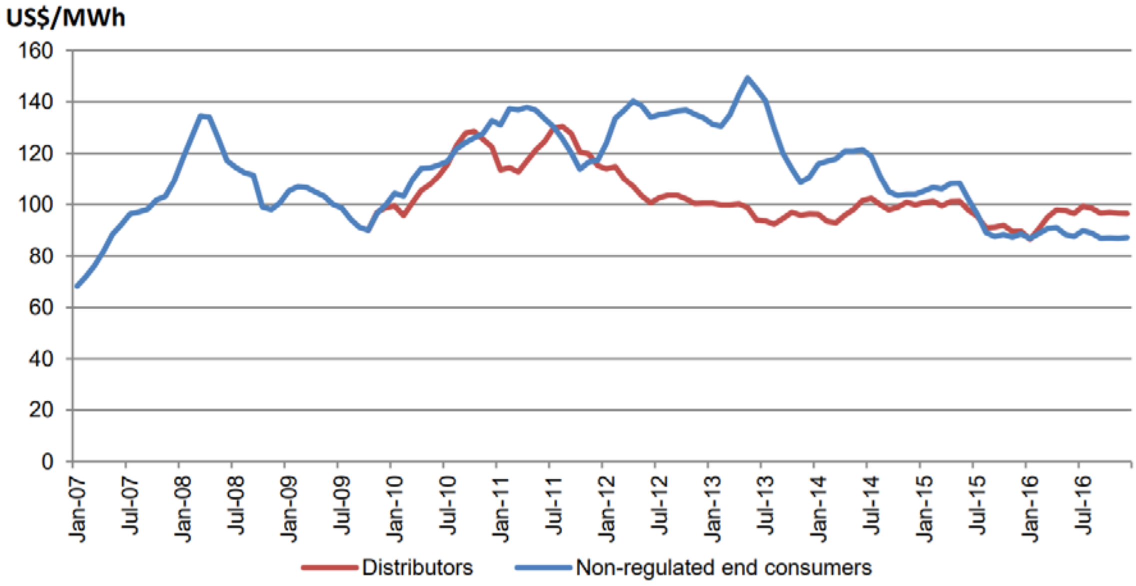
	2023	2035
100% RES LCOE:	72.7 $/MWh	56.4 $/MWh

Levelized costs of electricity for 2023 and 2035.

Depending on the split between hydrogen related and no-hydrogen related LCOE for the 100 % renewable energy vision, the range is as follows:

- For hydrogen-related electricity:
  - 28.4 to 56.2 $/MWh in 2023;
  - 21.4 to 56.4 $/MWh in 2035.
- For no hydrogen-related electricity:
  - 56.2 to 68.7 $/MWh in 2023;
  - 56.4 to 64.2 $/MWh in 2035.

The current LCOE (2016) of the system fluctuates in the range of 81.8 $/MWh and 86.7 $/MWh, depending on whether the installed capacity of diesel plants that function as backup is incorporated into the leveled electricity cost o not. In addition, for comparison purposes, the following figure shows the average market price for unregulated customers and distributors in Chile from 2007 to 2016.



Mean market price for non-regulated clients and distributors[6].

[6] Obtained from the study: “Diseño del mercado para gran participación de generación variable en el sistema eléctrico de Chile” from Generadoras de Chile A.G.

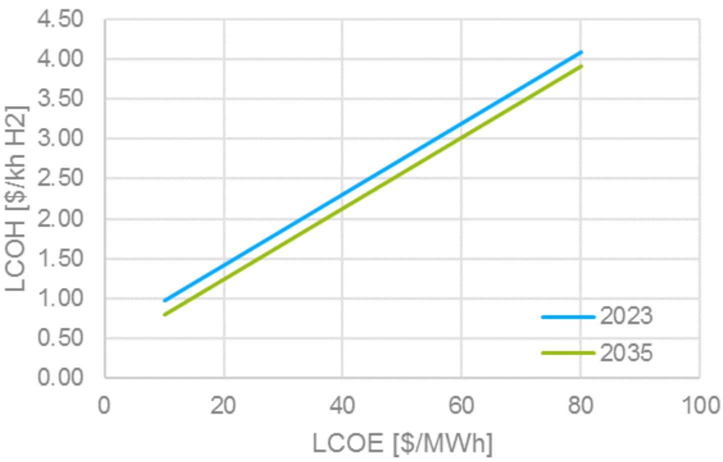
As observed, the projection of the LCOE for the 100% Renewable scenario to the year 2035 presented a decrease of close to 30% compared to the LCOE of the current system.

Levelized cost of hydrogen

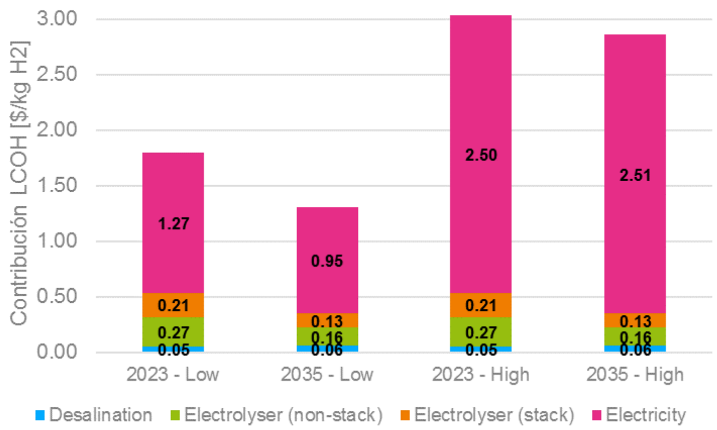
The cost of producing green hydrogen via electrolysis within the 100% renewable vision was calculated. Following the previous split for hydrogen-related electricity, the value of the LCOH lies within the following interval:

- 1.8 to 3.0 $/kgH2 in 2023;
- 1.3 to 2.9 $/kgH2 in 2035.

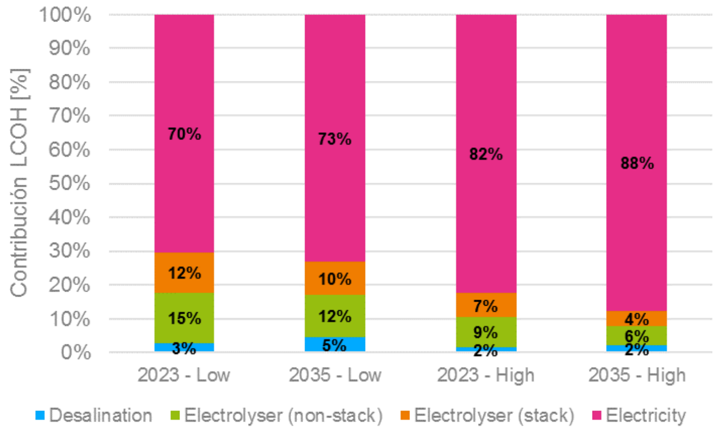
Such costs lie in the range of competitivity compared to other studies performed by international entities in different zones of the world. As depicted on the next figures, the impact of the electricity cost in the LCOH is between 70 and 88 % Therefore, the correlation between LCOE and LCOH is fundamental for the competitiveness of electrolyser-produced hydrogen.



LCOH in function of LCOE for 2023 and 2035.



Contribution of the upstream building blocks of the hydrogen value chain for LCO_{High} and $LCOH_{Low}$ in 2023 and 2035.



Contribution of the upstream building blocks of the hydrogen value chain for LCO_{High} and $LCOH_{Low}$ in 2023 and 2035.

Screening of the renewable hydrogen applications

For the hydrogen-related applications, the competitiveness is assessed by comparing to the conventional alternative. The following applications have been assessed:

- Fuel cells for heavy-duty transport;
- Fuel cells for railway applications;
- Hydrogen-diesel blending for heavy-duty transport;
- Hydrogen as a fuel substitute for thermal applications;
- Hydrogen as a substitute for LPG for heating applications;
- Hydrogen as a substitute for natural gas as a reducing agent;
- Renewable hydrogen for producing renewable ammonia.

The assessment is performed for both time horizons, i.e. 2023 and 2035. Despite the substantial differences in techno-economic parameters, the three most promising applications remain the same, namely: **fuel cells for heavy-duty transport, hydrogen-diesel blending for heavy-duty transport, and hydrogen as a substitute for LPG.**

Screening of the non-hydrogen applications

The renewable energy vision encompasses the entire energy supply, and therefore, the following business cases are assessed as well:

- Renewable electricity for substituting not fully-renewable electricity;
- Renewable electricity for substituting gasoline in passenger vehicles;
- Renewable electricity for substituting diesel in stationary applications;
- Low-temperature solar thermal applications for substituting diesel;
- High-temperature solar thermal applications for substituting fuel oil and coke.

For both time horizons, two applications are the most promising, namely: **renewable electricity for substituting gasoline in passenger vehicles and renewable electricity for substituting diesel in stationary applications**.

Besides these two applications, it was already mentioned that the LCOE for the 100 % renewable energy vision results in a lower LCOE in 2023 and 2035 than the BAU in 2023. Therefore, **renewable electricity as a substitute for not fully-renewable electricity** can be considered as a competitive option as well. Also, **high-temperature solar thermal for substituting fuel oil** shows potential as a competitive option.

Short-term and long-term opportunities

A summary is constructed with the operating expense margins calculated for each case analyzed. The margins in the OPEX are a good indicator of how promising a case is, by showing the potential operational margin to recover the fixed costs. If the OPEX margin is zero or negative, the business case will have more difficulties to be successful.

Based upon the most promising cases, the short-term and long-term opportunities were identified. The short-term opportunities are the ones that are technologically mature and commercially viable in the following years.

Hydrogen business opportunities

H2 margin	2023		2035	
	$LCOH_{high}$	$LCOH_{low}$	$LCOH_{high}$	$LCOH_{low}$
Fuel (base) → Hydrogen (fuel cell)	3%	43%	29%	68%
Fuel (total) → Hydrogen (fuel cell)	38%	63%	53%	79%
Fuel (base) → Hydrogen (blending)	-28%	18%	-2%	54%
Fuel (total) → Hydrogen (blending)	11%	47%	33%	69%
Enap 6 → Hydrogen (heat)	-42%	-3%	-19%	44%
Diesel → Hydrogen (heat)	-28%	18%	-2%	54%
LPG → Hydrogen	17%	51%	21%	64%
Natural gas → Hydrogen (reducing agent)	-60%	-32%	-53%	3%
Green ammonia	-25%	17%	-15%	42%

Non-hydrogen business opportunities

LCOE margin	2023		2035	
	$LCOE_{RES}$	$LCOE_{RES}$ w/o H2	$LCOE_{RES}$	$LCOE_{RES}$ w/o H2
Electricity (LCOE 2016 with backup diesel plants) → RES electricity	35%	35%	21%	26%
Electricity (LCOE 2016 without backup diesel plants) → RES electricity	31%	31%	16%	21%
Diesel → RES electricity	67%	60%	74%	71%
Gasoline (base) → RES electricity (Elec vehicle)	74%	68%	80%	77%
Gasoline (total) → RES electricity (Elec vehicle)	87%	84%	89%	87%
	LCOHeat (high T)		LCOHeat (high T)	
Enap 6 → high-temperature solar thermal	-		34%	
Coke → high-temperature solar thermal	-		-71%	
	LCOHeat (low T)		LCOHeat (low T)	
Fuel → low-temperature solar thermal	-72%		-27%	

The comparative summary with the operational expenditure margin of all business scenarios analysed with a colour code to highlight its level of competitiveness. **Green** means highly competitive, **yellow** means slightly competitive and **orange** means non-competitive **red** means highly non-competitive compared to the conventional method.

The following **short-term opportunities** are identified, in order of relevance:

- **Renewable electricity for substituting gasoline in passenger vehicles.** Electric vehicles are already commercially available today. With new electric vehicles being introduced, the driving range is increasing, and the CAPEX premium compared to gasoline vehicles is decreasing rapidly.
- **Hydrogen for heavy-duty transport.** Two main paths can be followed for the adoption of hydrogen in heavy duty vehicles, (1) the use of fuel cells and (2) dual combustion. Companies such as Ballard or Hydrogenics are producing fuel cells in MW sizes for trucks and trains. Trucks with diesel engines can be reconverted so that they can operate with hydrogen/diesel blending with currently available technology (e.g. Alset GmbH and HyTech Power). In this way, a significant fraction of diesel demand can be replaced in the short term.
- **Hydrogen as a substitute for LPG in heating applications.** For heating applications, the first hydrogen-fuelled appliances are being introduced into the market, indicating the technological maturity. Nevertheless, the hydrogen demand of this application is relatively small compared to the two abovementioned mobility-related applications.

Some of the applications will need more time to be implemented, due to the technical maturity, the time for implementation, commercial availability etc. The following **long-term opportunities** are identified, in order of relevance:

- **Renewable electricity for substituting diesel in stationary applications.** The technology for electrifying stationary diesel-fuelled applications is available, and a large share of this application has been electrified already. However, for the cases that have been not electrified yet, it indicates there are still some barriers. Furthermore, the hydrogen is relatively small compared to the other long-term opportunities.
- **Hydrogen fuel cells for heavy-duty transport.** In the long term, fuel cells have the advantage over hydrogen-fuelled combustion engines due to the increased energy efficiency, resulting in an improved operational competitiveness. With fuel cell technology maturing in the long term, and the CAPEX reducing accordingly, this operational competitiveness will translate in an overall cost competitiveness.
- **Renewable electricity as a substitute for non-fully renewable electricity.** The LCOE for a fully-renewable energy system would be lower than the LCOE for the BAU in 2023, and the hydrogen-related electricity demand would be large. However, the required massive investments in renewable energy infrastructure will require many years to be realized.

Two other applications, which are especially relevant for Chile, offer a long-term business opportunity under certain conditions:

- **Green Ammonia.** Today, all ammonia is imported into Chile, which is used for manufacturing explosives for the mining industry. As this is a strategic industry for Antofagasta and Atacama, there is an interest in mastering the entire value chain. In the long-term and under the low LCOH scenario for hydrogen related electricity production, ammonia can be produced in a cost-competitive manner in Chile with renewable hydrogen.
- **High-temperature solar thermal applications.** In the long-term, for the smelting process of the mining industry an opportunity is identified for shifting from conventional fuels toward high-temperature solar thermal applications with the introduction of high temperature particle receiver technology for the thermal application. As these applications could supply a noticeable fraction of the energy requirements of the mining sector in a renewable manner, it is worth considering.

Conclusions, Recommendations, and Limitations

Conclusions

The development towards a 100% renewable scenario in the northern regions of Chile will be dominated by CSP and PV

The largest investments in electricity generation assets are in PV and CSP technology. Photovoltaic solar provides the lowest cost of electricity that is consumed during sunny hours (no battery storage is required). Additionally, CSP provides the lowest disposable energy cost thanks to the thermal storage capacity to provide electricity in hours without solar resource.

Given the excellent solar irradiation levels in the northern regions, the combination of PV and CSP results in the lowest LCOE of all renewable technologies. The electrical demand that can be supplied directly with PV energy is the lowest cost option, for demand in hours where there is no solar resource, CSP is the cheapest solution.

The production of hydrogen is made from PV generation.

The results of the long-term capacity expansion model indicate that hydrogen is produced by electrolysers only during sun hours with electricity produced by PV parks. This intermittent operation is more cost optimal than having electrolysers producing base hydrogen (24/7) with renewable energy from a PV and CSP mix.

This implies that the infrastructure to produce hydrogen can be developed independently of the electrical infrastructure because the electrolysers can be fed with a dedicated PV plant. In this way any change in the demand for hydrogen will not impact the development of renewable electricity generation infrastructure and vice versa.

The renewable potential of the northern regions largely exceeds local needs.

The Atacama Desert area needed to decarbonize the northern regions and to deliver more than a third of the electricity demand of the rest of Chile is less than 1 %. This means that there is a high potential for a greater incorporation of PV and/or CSP. As a result, the long-term capacity expansion model indicates the sequential installation of CSP and PV to provide renewable energy to the rest of Chile. The combination of CSP and PV produces surplus electricity during the day and night, maximizing the amount of energy that can be used by the rest of Chile.

The main short-term opportunities are related to mobility.

Diesel/hydrogen blending for high-tonnage trucks offers a great opportunity to replace a significant fraction of diesel demand in the short term by converting existing diesel engines to support blending. Furthermore, several truck manufacturers are planning to introduce their first fuel-cell electric trucks into the market in the coming years.

For passenger vehicles, the incorporation of electric vehicles and batteries can replace internal combustion engines in the short term, there is also a wide range of these commercially available vehicles at affordable prices with great autonomy.

The greatest long-term opportunities are dominated by mobility and the production of 100 % renewable electricity.

Fuel cell vehicles offer the opportunity to replace all fossil fuels in high-tonnage trucks, assuming a mature commercial availability in the long-term. Compared to hydrogen-fueled combustion engines, fuel cells offer the advantage of a higher energy conversion efficiency. For mobility applications with low energy consumption, electric vehicles with batteries are a better option.

The transition to a 100 % renewable system, which is mainly based on the combination of PV and CSP, is a cost-effective option in the long-term. This is due to the large amount of investments in infrastructure several years are required to be carried out. In any case, these must begin in the short term to reach the final objective.

The production of green ammonia and applications of high temperature solar thermal energy represent potential long-term opportunities with special interest in Antofagasta and Atacama.

Under certain scenarios, business cases for green ammonia production and high temperature solar thermal applications provide a positive operating margin. As both applications are highly related to the mining industry, they represent a great opportunity to be considered in both regions.

Recommendations

Wind Resource Sensitivity Analysis

As mentioned in the limitations, the wind resource was modeled with an average profile per node (Antofagasta, Atacama and the rest of Chile). This simplification excludes sites with high plant factors ("hot spots") of the selected optimal mix, sites that can represent poles of development for each technology. In this way, it is recommended to improve the model by adding several wind profiles that represent the regional hot spots to evaluate how the optimal combination of solar and wind resources impacts the behavior of the system.

CSP storage profile and flexibility

The CSP was modeled with an E2P ratio and a fixed production profile, which is conservative and does not demonstrate the advantages it can incorporate into the system with different values. The effective production of a CSP plant may consider some flexibility in order to better complement other sources of renewable energy with greater variability (such as PV and wind). This way there is space to optimize the size of the storage and the production profile, being able to reduce the global LCOE.

Regions with an excess of renewable energy

Delivering renewable energy to the rest of Chile is a great incentive to investments in Antofagasta and Atacama, in this way, we can evaluate what would be the impact of not considering the export of electricity, in order to determine the optimal combination of assets to do both self-sufficient regions.

Conversely, a more aggressive scenario aimed at producing electricity in the north to be used in regions of the rest of Chile, considering additional investments in transmission capacity, can assess what is the total energy export potential.

Model of hydrogen production and demand profile

In the model, monthly hydrogen production and demand coincide if the transmission and storage infrastructure have sufficient buffer capacity. A detailed analysis of the production and hourly demand would determine the storage capacity required (only the hourly hydrogen production was calculated in the model).

For demand, some applications have the flexibility to determine the minimum storage capacity of hydrogen. For example, hydrogen charging stations for mobility have high pressure tanks for gas storage, because vehicles need hydrogen at a higher pressure than necessary in the transmission media (pipes, tube trailers, etc). In this way the stations would have the flexibility to replenish the ponds, which can optimize the need for storage size in the intermediate chain.

Once an hourly hydrogen demand is considered, and all the sources of flexibility on the storage are applied, synergies between the electrical and non-electrical parts of the system will be observed. Providing hourly baseload of hydrogen can be performed either by integrating a transport and storage infrastructure of hydrogen or by developing even more the electrical infrastructure of the regions. The exact mix of both infrastructures can be optimized from a systemic point of view, in which interaction of both vectors takes place. For instance, if the electricity demand is high enough, the projected inversion on electric infrastructure for the 100% RES scenario could be enough to provide a part of this hourly hydrogen, reducing the need of storage infrastructure.

Evaluation of the cost of hydrogen infrastructure

In this study, only the hydrogen value chain was modeled until the production of hydrogen at the exit of the electrolysers. Therefore, to assess the full cost of hydrogen, intermediate costs related to compression, transmission and storage should be considered. These additional costs will impact the LCOH to be compared with conventional solutions. Additionally, the cost evaluation will indicate the need for investment in infrastructure in the intermediate value chain of hydrogen.

Additional costs in the hydrogen value chain of the most promising cases

Additional costs should be considered for the evaluation of business cases, for example, for the mobility associated with special vehicles from fuel cells, the necessary investment in service stations for hydrogen recharge or the cost of converting them should be considered. a diesel engine to operate with blending. These costs are allocated to the final part of the hydrogen value chain, which must be analyzed in detail for each attractive business opportunity identified in this report, in order to evaluate the impact of the additional investments required in each case.

Detailed analysis of the production of green ammonia and applications of high temperature solar thermal energy.

Due to the importance of ammonia as a chemical used for the production of explosives in the mining industry, it is interesting to investigate in more detail the local production of ammonia based on renewable energy. As the analysis indicated, the competitive margin is not as high as other applications, however, it can be competitive for certain scenarios. Antofagasta and Atacama can position themselves as the green ammonia producing regions, first for their own supply, and then export to regions with fewer renewable resources in the future. In addition to its use in explosives, ammonia is used as a raw material for fertilizers, which can become a future renewable product to be exported.

To produce the demand for high temperature heat from mining and industry, the introduction of high temperature receiver towers of the "falling-particle receiver" type was considered as an alternative to the consumption of fossil fuels for heat. This technology has the potential to lower the costs of solar thermal and CSP for applications that require high temperatures, however, the level of development is low. Chile can participate in the development of this technology at the level of research and the realization of pilot projects, in order to make feasible the introduction in the long term in the mining and industrial sector.

Opportunity for the export of hydrogen

In this report, the demand and production of hydrogen are only analyzed for the regions of Antofagasta and Atacama. Due to the high solar potential of the Atacama Desert, both regions could produce green hydrogen not only for Chile but to export it to other countries, being able to be key players in global gas and fuel markets with the comparative advantage of coming from renewable sources.

Limitations

Simplified wind resource model

As in the model a representative profile was considered for each renewable resource by region, some "hot spots" with high factors of wind power plants were ignored from the optimal cost solution for the 100% RES scenario. Under this simplification the investments in wind energy may have been underestimated and consequently replaced by investments in solar energy, however, if there is a greater fraction of wind power as part of the overall optimal cost solution, this would be lower than the one determined without wind. With this, the LCOE estimated in this study would be lower, improving the business cases investigated.

Simplified model of the other regions of Chile

As the scope of the study was limited to the regions of Antofagasta and Atacama, the interaction with the rest of the regions of Chile was modeled in a less detailed way. The decision to model the interaction of these two regions with the rest of Chile was to qualitatively evaluate the surplus characteristic in renewable energy of northern Chile and its potential export to other regions.

A detailed modeling of the rest of Chile can identify opportunities to import renewable energy from southern Chile (contrary to what was identified in the 100% RES scenario). Consequently, this would result in a lower investment in solar energy in Antofagasta and Atacama, however, the same situation identified with the wind profiles would occur: If the optimal cost solution considers import of renewable energy from southern Chile, the overall cost would be Therefore, the LCOE would be lower, increasing the competitiveness of the business cases analyzed.

Green hydrogen can be produced for export to the rest of Chile by pipelines or by ships to other countries. For the first, a pipe network must be built, in which the associated cost must be less than the cost of green hydrogen production locally in the rest of Chile (in this comparison, the associated costs must be considered in the hydrogen value chain). compression, storage and distribution to the south of Chile). For export to other countries, hydrogen carrier technologies must mature in order to be commercially available so that hydrogen can be transported to regions where local production is not competitive and willing to pay for importation.

Imperfect predictions

The long-term capacity expansion model used for the 100% RES scenario assumes perfect forecasts of renewable resources and energy demand, thus, the dispatch of the reservoirs in southern Chile is done in a way that complements the solar production of the northern regions. The reservoirs are used to compensate for the interannual fluctuations of the solar resource considering its maximum and minimum level.

Because there is no perfect long-term prediction, there are strict operational limitations for the dispatch of the hydropower water reservoirs, in which the opportunity cost of using water at a is priced. This will impact the available flexibility of the hydroelectric power plants, compared to the case with perfect prediction.