Solar NH_3-Pool Chile:

Concepts for the development of a sustainable green hydrogen/ammonia industrial park in the Antofagasta region (Chile).

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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The International Hydrogen Promotion Program (H2Uppp) of the Federal Ministry for Economic Affairs and Climate Protection (BMWK) of Germany promotes projects and the development of the green hydrogen market in certain developing and emerging countries as part of the National Hydrogen Strategy.

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Santiago, Abril 2024

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List of Abbreviations

Abbreviations	Full Name
AWE	Alkaline Electrolysis
BCN	Library of the National Congress of Chile
BEI	European Investment Bank
BESS	Battery Energy Storage Systems
BID	Inter-American Development Bank
BMWK	Federal Ministry for Economic Affairs and Climate Action of Germany
CAPEX	Capital Expenses
CBAM	Carbon Border Adjustment Mechanism
CIPP	Pecém Industrial and Port Complex
CNE	Nacional Energy Commission
Co2	Carbon Dioxide
COCHILCO	Chilean Copper Commission
CODELCO	Chilean National Copper Corporation
CORFO	Chilean National Production Corporation
CPM	Mejillones Port Complex
DDU	Urban Development Division
DIA	Environmental Impact Declaration
EIA	Environmental Impact Study
FERRONOR	Chilean Railway Transport Company S.A.
GEI	Greenhouse Gases
GHI	Global horizontal irradiation
GH2	Green Hydrogen
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
H2	Hydrogen
H2V	Green Hydrogen
KfW	German Development Bank
KOH	Potassium Hydroxide
LCOA	Levelized Ammonia Production Costs
LCOE	Levelized cost of electricity
LCOH	Levelized Costs of Hydrogen Production
MINVU	Chilean Ministry of housing and urbanism
MW	Mega Watts
NDA	Confidentiality Agreement
NH3	Ammonia
OGUC	General Urban Planning and Construction Ordinance
OPEX	Operating costs
PEM	Proton exchange
PPA	*Power Purchase Agreement*
PPP	Public Private Collaboration
PRIBCA	Intercommunal Regulatory Plan for the Coastal Edge of the Antofagasta Region
PSA	Pressure swing adsorption
RED II	European Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
SAF	Sustainable Aviation Fuel
SCDI	Namibia Southern Corridor Development Initiative
SEC	Superintendency of Electricity and Fuels

SEIA	Environmental Impact Assessment Service
SEN	Chilean National Electric System
SOEC	High temperature electrolysis
SPV	Special Purpose Vehicle
TGN	North Bulk Terminal
EU	European Union
UNIDO	United Nations Industrial Development Organization
ZAP	Port Air Zone

Executive summary

This report presents the main results of the project entitled "SolarNH3-Pool Chile: Concepts for the development of a sustainable industrial park for green hydrogen/ammonia in the Antofagasta region (Chile)", developed by a consortium formed by the companies Soventix Chile SpA, SI Solar Investments GmbH, and Pabettin GmbH, in collaboration with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH within the framework of the H2Uppp Program. This public-private partnership (PPP) project involves the development of a series of studies aimed at developing an innovative and replicable proposal, contributing to the conceptualization of an industrial park for green hydrogen and derivatives in Mejillones, promoting the shared use of enabling infrastructure to enhance the competitiveness and sustainability of the nascent green hydrogen and derivatives industry in the Antofagasta region.

To establish the foundations of the proposal, a conceptualization of an industrial park for green hydrogen and derivatives was developed, also examining applicable public policies and regulatory frameworks for this industry. International experiences were also reviewed to extract useful lessons for this work. These foundations were complemented by an analysis of regional infrastructure, specifically in the commune of Mejillones, including port terminals, seawater desalination plants, road and rail networks, electrical transmission networks, gas pipelines, among others.

Based on the above results, a proposal for a master plan for the sustainable long-term development of an industrial park in the commune of Mejillones was developed, providing a dimensioning of the required land surfaces, along with a reference planning of the necessary common infrastructure, to provide a guiding vision and support for a strategic land reserve. The master plan is conceived as a contribution to land planning, facilitating the efficient use of infrastructure, land, and the coastline, contributing to mitigating the negative environmental impacts of projects. The proposal also offers several advantages for individual projects located within the industrial park, such as reduced investment and operating costs, expedited access to land, shorter permit acquisition times, and thus lower development and financing risks.

Furthermore, this report developed the conceptual design of a model green ammonia production plant in the proposed industrial park. Using a systematic approach to optimizing the entire value chain, this design allowed estimating the CAPEX and OPEX of the model plant and thus the levelized costs of hydrogen (LCOH) and ammonia (LCOA) production. The design envisages a project development in two stages, to take advantage of economies of scale in production processes. The first stage involves a production capacity of 1,000 tons/day (320 kton/year equivalent), with a doubling of capacity in the second stage reaching 2,000 tons/day.

The economic results obtained are positive in terms of the levelized costs of ammonia production (LCOA), which are considered competitive compared to average prices in the international gray ammonia market. Considering the additional income flows from the project's commercialization of by-products (such as oxygen, renewable energy surpluses, carbon credit sales), production costs (LCOA) in the range of 600 to 800 USD/ton of ammonia can be achieved, with levelized hydrogen costs (LCOH) in the range of 3.5 to 4.0 USD/kg.

This project involved collaboration and consultation with different actors from the public, private, financial, and academic/research sectors from the outset, with the aim of validating the relevance of the proposals and contributing to knowledge transfer and human capital formation. This work concludes with recommendations to advance towards an implementation stage of the industrial park proposal in Mejillones, including the timely land reservation and the design of an appropriate park governance model. For this stage, it is deemed pertinent to consider as a reference the guidelines developed by the United Nations Industrial Development Organization (UNIDO, 2021) for the design of industrial eco-parks.

Introduction

Public-Private Project Solar NH3-Pool Chile

On behalf of the BMWK, the "International Hydrogen Ramp-Up Programme" (H2Uppp), implemented by the German International Cooperation Agency (GIZ), supports the expansion and development of green hydrogen (GH2) markets and its derivatives, referred to as PtX products, in certain developing and emerging countries. Chile is one of the partner countries of H2Uppp and has the potential to become a global player in green hydrogen production, domestic use, and export, due to its high potential for renewable energy. In this context, the evolution of the green hydrogen market, both in Chile and globally, is becoming increasingly dynamic. Emerging and developing countries need specific support to identify economic pathways for production and use, project opportunities along the value chain, develop business models, as well as improve their regulatory framework for GH2 and PtX products.

The present report offers the main results of the project *"SolarNH3-Pool Chile: Concepts for the development of a sustainable green hydrogen/ammonia industrial park in the Antofagasta region (Chile),"* developed between November 15, 2022, and February 29, 2024, by a consortium formed by the companies Soventix Chile SpA, SI Solar Investments GmbH, and Pabettin GmbH, in collaboration with GIZ under the H2Uppp Program.

Soventix Chile is a subsidiary of Soventix GmbH, based in Wesel, Germany. The Soventix group operates in 9 countries on 4 continents and has over 12 years of experience in the renewable energy sector. Soventix Chile SpA has established itself in the photovoltaic industry in Chile and other South American countries, as a highly qualified partner with a wide range of services in consultancy, development, planning, and project financing, as well as turnkey construction, site supervision, operation, and maintenance of solar parks.

SI Solar Investments GmbH, based in Switzerland, is dedicated to the development of projects in the solar sector. It currently develops 500 MW of ground-mounted projects and 50 MW of rooftop projects. This company also participates in innovative projects such as agro-photovoltaic, community energy photovoltaic projects, and hydrogen production projects.

Pabettin GmbH, based in Germany, has international experience since 2014 in the development, financing structuring and construction of photovoltaic solar parks. It has completed around twenty ground-mounted solar parks with local and international partners, including several projects in Chile.

The development of green hydrogen and its derivatives (e.g., green ammonia) “industrial parks” can play an essential role in the cost-efficient and sustainable development of a hydrogen economy. By pooling ammonia production plants, several medium-sized companies with lower production capacities can collectively generate economies of scale for competitive ammonia production and marketing for export, as well as for local use.

Given the early stage of the industry, investors, and future companies wishing to participate in the sector, face high financial risk if they act individually, given the need to create large production capacities to achieve competitive prices on an international scale. The strategic planning of a grouping of plants, i.e., an industrial park, for green hydrogen leads to a lower investment required for each project, generating market openness and, therefore, project realization.

Coordination of several medium-scale production projects with common infrastructure is essential to produce and export hydrogen or ammonia from the industrial park. Shared infrastructures can reduce the specific costs of each project and avoid the construction of unnecessary infrastructure. Additionally, by optimizing the infrastructure design to include various projects, environmental impacts can be minimized.

The concept of industrial parks for green hydrogen gains more weight in regions where there are ports with international services and favorable renewable energy conditions. Antofagasta offers a special opportunity to exploit this potential and thus create added value for the region.

Objectives and approach

The commitment to advancing the green hydrogen industry is exemplified by the public-private collaboration between GIZ and the consortium led by Soventix Chile SpA with the purpose of contributing to the development of a green hydrogen and derivatives industrial park in the Antofagasta region, specifically in the Mejillones municipality, and to achieve national decarbonization and climate protection goals.

This project is being carried out in the initial stage of development for the green hydrogen and derivatives industry in Chile, where approximately 64 projects were publicly announced, mainly in the regions of Antofagasta and Magallanes. These projects are being developed independently, seeking to take advantage of the availability of good-quality renewable energy resources, but independently addressing their infrastructure requirements. There is a need for proper territorial planning to better utilize the land, make better use of common-use infrastructure to reduce project investment costs, leverage synergies to reduce operating costs, and minimize negative environmental impacts.

Under the H2Uppp program, the two companies have developed a series of studies/actions:

- The conceptualization and sustainable development of a green hydrogen and derivatives industrial park in the Mejillones municipality, Antofagasta region, based on the utilization of synergies and shared use of existing and planned regional infrastructure.
- Pre-design, at a conceptual level, of a model green hydrogen and ammonia production plant, with a preliminary technical-economic analysis for the configuration and sizing of the different elements of the value chain of this plant.
- Fostering relationships and collaboration with local and regional authorities, local communities, the public and private sectors, and academic circles, among others, and thus contributing to the transfer of knowledge, learning, and advanced human capital formation for this new industry.

This public-private partnership project (PPP) develops a concrete and innovative proposal, contributing to the conceptualization of an industrial park for green hydrogen and derivatives in Mejillones, thus promoting shared use of enabling infrastructure and leveraging synergies to improve project competitiveness and sustainability. The respective studies were conducted by specialists from the consortium led by Soventix SpA and specialized subcontracted consultants. Hinicio conducted consultations on the general master plan of the industrial park and the pre-design of a green ammonia model plant within it, First Climate addressed carbon footprint and carbon finance contribution, and Inodú carried out an analysis and conceptual pre-design of the corresponding shared infrastructure.

Report structure

The content of the present report is structured into the following chapters:

- The first chapter addresses the fundamentals and the conceptualization of an industrial park for GH2, analyzing existing public policies and the national institutional framework, as well as the regulatory framework for the development of an H2/NH3 asset pool. Synergies and economies of scale analysis in the green hydrogen/ammonia value chain and business model/contractual structures for the establishment of an industrial park are studied. Finally, similar international experiences are presented.

- The second chapter analyzes enabling infrastructure and logistics in Antofagasta and specifically in the Mejillones municipality. An inventory of relevant regional infrastructure for hydrogen and ammonia supply chains and logistics (port, transportation and storage capacity, railway and loading stations, among others) is presented. It also includes measures to improve regional infrastructure to optimize logistics and transportation costs for hydrogen and ammonia projects. A solutions and business models' approach are made to optimize renewable energy supply. Likewise, approaches to solutions and business models for optimizing the water supply of the plant park (seawater desalination plants) for greater sustainability and economic efficiency are presented.

- The third chapter develops a master plan for the industrial park in the Mejillones municipality, obtaining the sizing of the required land surfaces, together with a referential planning of the necessary common infrastructure and viable location alternatives for the park.
- The fourth chapter presents a conceptual design of a green ammonia model plant in the proposed industrial park. An evaluation and selection of technologies for the main plants is included, the production system and its capacities are optimized, and a plant concept for two stages of development is elaborated: the sizing of its equipment and plants, investment and operating costs, and main results in levelized production costs.
- The fifth chapter presents the various collaborations established with the public, private, financial, and academic/research sectors and how they contributed to knowledge transfer in the region and internationally.
- Finally, the report concludes with a summary of the main findings and recommendations.

1 Fundamentals and conceptualization of the project

1.1 Public policies and national institutional framework

Since the last decade of the 20th century, Chile has experienced significant growth in its energy demand, primarily driven by industrial development and population growth. This growth has led to increased dependence on fossil fuels, especially coal and oil, for electricity generation, resulting in an increase in greenhouse gas emissions. It is in this context that Chile began to promote a transition towards a cleaner and more diversified energy system based on the international Paris Agreement, captured in the document "Energía 2050: Política Enérgetica de Chile", year 2022.

In November 2020, the Ministry of Energy of Chile published the "Estrategia Nacional de Hidrógeno Verde" ("National Green Hydrogen Strategy") defining the vision, objectives, strategic pillars, and general action plan for the development of the green hydrogen and derivatives industry in Chile. The strategy highlights the advantages that Chile presents for this new industry, further emphasizing its role in energy transition and in achieving economy decarbonization goals, laying the groundwork to direct the work of the public sector towards promoting industry development.

The action plan, included in the National Green Hydrogen Strategy, encompasses 4 approaches with 3 specific measures to be carried out for each one. One of these measures specifically addresses territorial planning and resource use:

"We will evaluate the opportunities and challenges of green hydrogen in policies, regulations, and territorial plans*. Considerations will be analyzed regarding the inclusion of the green hydrogen value chain in the development processes of policies and territorial plans in various regions. This will facilitate proper territorial integration and rational use of our land and natural resources, considering synergies and interactions with other activities and human requirements, such as water use."* (Added emphasis)

According to the excerpt, and considering this measure, the need for sustainable development of this new industry and its harmonious integration with communities is evident, with "policies, regulations, and territorial plans" being relevant.

In line with the National Green Hydrogen Strategy, the "Green Hydrogen Industry Development Committee" was established in 2022 under resolution 60/2022 of the Ministry of Economy, Development, and Tourism through the Corporation for Production Development (CORFO) for its implementation. This resolution details the main functions of the committee, including the elaboration of action plans, in accordance with the progress and performance of the aforementioned strategy; managing initiatives, activities, and programs promoted by the State for the development of the GH2 industry; proposing research lines with development in innovation and promotion of the green hydrogen industry; and providing support in the design of promotion instruments, productive or business innovation, and financing (BCN, 2022). These functions are directly relevant to the development of projects of this type.

During the year 2023, the draft of the "Green Hydrogen Action Plan 2023-2030" was developed in depth, defining its main objective:

"(…) to define and disseminate a roadmap between 2023 and 2030 that allows the deployment of a sustainable green hydrogen and derivatives industry, through coordinated actions among the various government portfolios and related agencies, in accordance with regional and local initiatives".

This development culminated in a participatory process, aimed at giving greater concreteness to the implementation of the National Hydrogen Strategy, reinforcing its character as a state policy.

The draft of the "Green Hydrogen Action Plan 2023-2030" was published in December 2023 and was available for public consultation until February 13, 2024. As of the date of the present report, the Ministry of Energy is in the process of developing the final document considering the consultative process of the document.

The draft action plan includes 111 measures addressing aspects of territorial planning, efficient use of public lands, and shared use of enabling infrastructure for the new hydrogen industry. The document also defines 30 "Highlighted Measures to Promote a Sustainable H2V and Derivatives Industry in Chile" addressing topics related to Investment Axis, Incentives and Institutional Framework, Sustainability, Local Value, and Infrastructure and Territorial Organization. Below are the highlighted measures that predominate over areas of public administration and territorial planning (Green Hydrogen Plan, 2023):

"2. Rapidly implement a plan to enable regulations for the industry.

9. Dispose of public lands to promote industry, promoting its sustainable development.

19. Timely develop various instruments that promote inter-ministerial and integrated planning of enabling infrastructure.

20. Develop plans and actions that promote shared infrastructure in different parts of the industry value chain, through coordination between various public and private actors.

22. Harmonize territorial planning instruments with the industry's challenges, prioritizing the Antofagasta, Valparaíso, and Biobío regions, and particularly the Mejillones municipality as a starting point.

24. Develop Strategic Energy Plans with Strategic Environmental Assessment in the Antofagasta and Magallanes and Chilean Antarctic regions, culminating both before 2025.

30. Develop and/or update regional roadmaps consistent with the Green Hydrogen Action Plan 2023-2030."

The proposals mentioned in the action plan are intended to be coordinated and completed by the year 2030. The first implementation timeframe (2023-2026) is designed to complete the necessary investment measures, norms, and regulations and to solidify relationships with potential offtakers. The second timeframe (2026-2030) is designed to achieve productive development and decarbonization with an emphasis on regional work and local development (Green Hydrogen Action Plan, 2023).

Additionally, the need to update the planned short-term measures is foreseen (by the end of 2024). Within the action plan it was stated, as the next step, the update of the "National Green Hydrogen Strategy", directing efforts towards an industrial policy for sustainable development once 5 years have passed since the publication of the action plan.

The development of the industrial park will be carried out in accordance with regulatory requirements and current regional plans and will be adjusted based on the regional plans implemented during the project execution. This includes considering and evaluating the implications of implementing the measures mentioned above in the industrial park.

It is relevant to note that the proposal for a green hydrogen industrial park in Mejillones can be understood as a concrete measure that allows for the direct implementation, in a specific location, of several of the more generic measures contained in the cited documents.

Furthermore, the draft action plan specifies the governance structure for the management and implementation of the policies and measures contained in it. This governance assigns specific roles to different public bodies, as well as decision-making instances, as shown in the following figure:

Figure 1. Governance of the Green Hydrogen Plan.

Source: (Green Hydrogen Action Plan, 2023).

A prominent role in this governance is played by the Ministry of Energy and CORFO. The former chairs the Interministerial Council, composed of 11 ministries, whose role is to direct the Industry Development Committee and coordinate and support the decisions and actions of public institutions within the framework of the Action Plan. CORFO serves as the Executive Secretariat of the Committee, with the role of implementing the development instruments included in the Action Plan and convening meetings of the Interministerial Council.

The governance described in greater detail in the cited document is relevant for coordinating with public bodies in the development and implementation of initiatives and projects related to the deployment of the green hydrogen industry, such as those outlined in the present Report.

In addition to the GH2 strategy and action plan, various initiatives have been developed within the framework of the country's public policies. Among these is the publication of evaluation criteria in the SEIA for GH2 projects, the publication of the "Framework Law on Climate Change," the "Window to the Future" initiative, and various financing programs.

Among the recent initiatives mentioned within the framework of public policies, particular attention is given to the technical document specifying the evaluation criteria in the SEIA for GH2 projects. It should be noted that "*the development of the GH2 industry does not necessarily involve the development of a single project in stages but rather consists of different types of projects that collectively describe the processes and subprocesses involved in the production of GH2, forming the GH2 value chain.*" Hence, *"the proponent must indicate which process or subprocess of the value chain the project or activity to be evaluated will cover, with the aim of limiting the environmental assessment solely to the parts, actions, and physical works of the project, and not to other processes or subprocesses of the value chain"* (SEA, 2023).

1.2 Applicable regulatory framework

In addition to identifying public policies and institutional frameworks, it is relevant to understand the regulatory framework applicable to hydrogen and derivative production methods, the products themselves, as well as their commercialization in international markets.

On one hand, this section analyzes the current national regulatory framework in Chile. It highlights the most relevant regulations, such as the Energy Efficiency Law and MINVU DDU 470. It also links measures to enable the green hydrogen industry, such as SEC for obtaining special permits for hydrogen projects or the announced regulatory measures of the Green Hydrogen Action Plan. On the other hand, the section reviews the European regulatory framework applicable to products such as green hydrogen or its derivatives to meet the European Union's climate goals.

Hydrogen has commonly been used as a raw material for the chemical industry, so there are regulations for handling this substance. Although there is currently no specific legal framework for green hydrogen, the country is developing and modifying legislation and regulation to respond to the needs of the growing green hydrogen industry. The creation of a green hydrogen regulatory framework is a state policy and is explicitly stated in the 2020 National Green Hydrogen Strategy.

Decree Law 2.224/1978 defines hydrogen as a "dangerous substance". This definition forced hydrogen to be subject to different regulatory agencies depending on its use, such as the Ministry of Health, the Ministry of Transportation and Telecommunications, the Ministry of Mining, among others. In 2021, the Energy Efficiency Law 21.305/2021 was enacted, which in its article 7 amends Decree Law No. 2.224/1978, creating the Ministry of Energy and the National Energy Commission.

Within the scope of these modifications, the competencies of the Ministry of Energy were modified, incorporating hydrogen and fuels from hydrogen, and other energy sources and vectors, as competencies of the Ministry of Energy (BCN, 2021). The result of this modification is placed in article 3 of Law No. 2.224/1978, which is quoted below:

"For the purposes of the authority that corresponds to the Ministry of Energy, the energy sector includes all activities of study, exploration, exploitation, generation, transmission, transportation, storage, distribution, consumption, efficient use, import, and export, and any other related to electricity, coal, gas, oil and derivatives, nuclear, geothermal, and solar energy, hydrogen and fuels from hydrogen, and other energy sources and energy vectors."

This update of the definition of hydrogen (and its derivatives) as an energy vector is consistent with European regulations. Furthermore, it has allowed the SEC to grant special permits to initiate and operate most hydrogen projects, except for special projects related to mining. For this purpose, the SEC and the Ministry of Energy have made available the "Support guide for the application for approval of special hydrogen projects".

In this regard, the guide aims to provide guidance on the implementation of hydrogen projects when they include any installation related to hydrogen production, conditioning, transportation, distribution, storage, or consumption. It also assists in preparing the necessary documentation folder for processing installation authorization requests to be submitted to the SEC (SEC, 2021).

In addition to regulation with a special focus on safety, it is important to consider regulation associated with territorial compatibility. For this, the MINVU issued a circular (Ord. No. 0504) from the Urban Development Division (DDU) 470/2022, titled "Land Use Applicable to Buildings, Installations, and Networks Associated with Hydrogen Generation". This circular defines the land use of green hydrogen and ammonia production projects according to the types defined in Article 2.1.29. of the General Urbanism and Construction Ordinance (OGUC).

It should be noted that when projects are aimed at hydrogen generation, their land use is defined as "Energy Infrastructure". Conversely, when projects are aimed at ammonia production, with hydrogen being only an input for its production, the type of land use is defined as "Productive Activities". This is illustrated by the following excerpts from DDU 470, as follows:

"Therefore, the networks or layouts of any of the components of the projects, as long as they are intended for the transport of hydrogen, will always be understood as admitted and will be subject to the provisions established by the competent bodies and the rules imposed by the legal system."(…).

"The installations and buildings corresponding to them must be qualified by the Regional Ministry of Health, in accordance with the provisions of the fifth paragraph of the aforementioned Article 2.1.29. of the OGUC."(...).

"Projects where the product obtained from such activity is a substance that is not part of the energy sector, in accordance with article 3 of Decree Law No. 2.224, of 1978, such as ammonia, with hydrogen being only an input for its production, correspond to the type of land use Productive Activities, for complying with the provisions of Article 2.1.28. of the OGUC."(…). .

In addition to existing legislative and regulatory aspects, the draft Green Hydrogen Action Plan 2023-2030 refers to "regulatory enablement and market standards" (Annex No. 1) and includes, among other measures, the "implementation of a work plan for enabling regulations for the hydrogen and derivatives industry" (Measure No. 3). Due to these announcements, it is expected that the update of a regulations work plan will be published along with the Action Plan.

In addition to the references, Annex No. 1 of this document presents a compilation of current regulations involving the production of green hydrogen and ammonia, directly or indirectly, as well as applicable international guides and regulations, including the government's draft regulations work plan.

In conclusion, developing an appropriate regulatory framework for the emerging green hydrogen and derivatives industry allows for the creation of legal security and certainty, enabling project development. Regulatory aspects related to the industrial classification of hydrogen and derivative production plants, associated territorial and environmental issues, as well as safety conditions in the production and logistics of products, are key to location and project design decisions and provide certainty to investments.

In addition to the national legal framework, it is relevant to consider the regulations applicable in the markets to which the products are intended for export. Europe emerges as a relevant consumer market, and to date, the European Union (EU) has implemented regulations for the inclusion of low-emission and renewable-origin products.

The Renewable Energy Directive (RED II, European Commission, 2018) entered into force in 2018. RED II establishes a general policy for the production and promotion of energy from renewable sources in the European Union. It also includes energy goals, aiming to achieve 32% of the total energy consumption in the EU from renewable sources by 2030. RED II defines non-biological renewable fuel (RFNBO), which includes renewable energy-based hydrogen and derivatives. With the proposed update, RED III will increase the share of renewable sources in total energy consumption to 42.5% by 2030 (RED III, European Commission 2023). Additionally, while RED II only considered RFNBOs as fuels for transportation, RED III extended the definition independently to the final end-use sector.

The delegated acts to Articles 27 and 28 of RED II provide relevant regulatory specifications to consider, such as detailed requirements for the supply of renewable electricity used to produce RFNBOs and the methodology for evaluating greenhouse gas emissions savings from RFNBOs, as well as the threshold for greenhouse gas emissions savings to be achieved. This regulatory framework applies to both production projects within the EU and projects seeking to export green hydrogen and/or its derivatives to Europe.

The relevant regulatory requirements to be met by the green hydrogen and derivatives value chain are presented below:

1. Additionality:

a. Until 1/1/2038, not applicable to facilities producing fuels before 1/1/2028.
b. The renewable plant has not been in operation for less than 36 months from the fuel installation.

c. The renewable plant has not received state subsidies or investment assistance, excluding support for land or grid connections.

2. Temporal correlation:

a. Until December 31, 2029: Electricity must be generated during the same month as the fuel production (monthly correlation).
b. From January 1, 2030: Electricity must be generated during the same hour as the fuel production, or from electricity stored in a new generation asset located behind the same connection point as the renewable or fuel plant, which was charged during the same hour the renewable plant generated electricity.
c. The temporal correlation criterion is considered fulfilled if the hourly marginal cost at which energy is taken from the grid is less than €20/MWh.

3. Geographic correlation:

a. The renewable plant and the fuel plant are in the same bidding zone.
b. Both plants are in interconnected areas, and the marginal costs at the fuel plant are lower or equal to those at the renewable plant.
c. The renewable plant is in interconnected marine bidding zones with the electrolyzer.

In consideration of these regulations, certifications for suitable green hydrogen and derivatives have begun to be developed to accredit compliance with the requirements. Various organizations are working to establish international certification schemes. These include CertifHy, which is in the pilot stage, I-REC, and the Ammonia Energy Association (AEA) certificate, both in development, among others.

Regarding its climate goals, the European Union has created the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2023), which allows for a fair price on carbon emissions during the production of products imported into the EU, ensuring that the carbon price on products equals that of local production. This will prevent a disadvantage for EU production compared to production in jurisdictions without a carbon price and promote more sustainable industrial production in non-EU countries. CBAM implementation will take place in two phases.

The first phase began on October 1, 2023, and only considers emissions reporting, without charges, for the cement, steel, aluminum, fertilizer, hydrogen, and electricity industries. By 2026, the mechanism will be fully operational.

In addition, through the recent update of emissions trading standards (ETS) (European Commission, 2024), the flaw that granted free emission rights to producers of fossil fuel-intensive industries but not to equivalent decarbonized projects has been corrected. Thus, producers of green hydrogen and derivatives will have the same eligibility for free emission rights under the ETS as producers of hydrogen and ammonia based on fossil fuels, and coke-based iron and steel production.

As a result, from 2025, producers of green hydrogen and steel will be able to claim and sell these credits, generating a new source of income. However, this opportunity will be temporary, as the EU is gradually phasing out free carbon emission rights as CBAM is introduced over the next ten years.

In conclusion, the Government of Chile is currently working on a robust legal framework to take advantage of the benefits of green hydrogen and its derivatives production in the country. Likewise, guidelines have been developed to facilitate the processing of projects seeking to produce green hydrogen and its derivatives. Additionally, the Regional Government of Antofagasta and the municipality of Mejillones are in the process of updating various territorial planning instruments, which should provide more legal certainty for projects wishing to install their plants in that area.

Regarding Europe, the European Renewable Energy Directive outlines the requirements that must be met to export green hydrogen and/or its derivatives to the EU. This document enables the development and use of certification schemes, which are essential for opening new international export markets for these products and for the design of industrial plants.

1.3 Conceptualization of a green hydrogen and derivatives industrial park

Chile has favorable technical and policy conditions (current and in development) for the green hydrogen and derivatives industry. This scenario has led to the announcement of several projects in the national territory, with concentrations observed in the northern, central, and southern zones, with the Antofagasta region being one of those with a larger portfolio of projects.

Antofagasta will host both larger-scale projects for international export purposes and intermediate-scale projects for industry and local hydrogen consumption. By mid-2023, 12 hydrogen projects have been identified in various stages of development in the region, totaling 8,650 MW of electrolysis by 2030 (Hinicio, 2023).

Several components of the green hydrogen and derivatives value chain have similar technical needs among projects. For example, projects may seek to produce the same final product for export, requiring storage and port infrastructure. However, infrastructure needs significantly increase the time and costs to develop projects. In addition to the financial risks involved, the isolated and uncoordinated development and construction of projects can be inefficient and unsustainable.

Considering the challenges, the proposal to develop a hydrogen industrial park emerges as an attractive solution. An industrial park is defined as a grouping of activities or projects, which may or may not be related to each other, enabling industrial development through planning and spatial limitations, such that activities are located on a shared and favorable property.

Industrial parks offer a range of services such as electricity supply, water supply with different types of treatment as per usage, among others. Globally, some industrial parks also offer tax incentives, depending on each country's regulations.

In this context, grouping industrial activities in an industrial park can be useful for providing services and products that complement each other. By sharing a common territory, distances for input supply, exchange of intermediate products, transportation of people and information are reduced. These facilities especially enable shared infrastructure among projects, leveraging economies of scale to make individual projects more economically viable. Besides enhancing economic performance, industrial parks should improve environmental and social performance through collaboration on environmental and resource challenges. Thus, industrial symbiosis will enable competitiveness and achieve sustainable development.

The state of the green hydrogen industry in Chile is conducive to planning, from the outset, the sustainable and competitive development of an industrial park for green hydrogen and derivatives. This work conceptualizes an industrial park for green hydrogen in Mejillones, in the Antofagasta region.

The concept of a green hydrogen industrial park involves a grouping of various productive plants producing different types of products and sizes, planned as a phased development (see Figure 2). The main products are green hydrogen and ammonia, as well as other derivatives (e.g., synthetic fuels) or products that can utilize these chemicals as inputs, such as urea, nitrogen fertilizers, explosives, among others. In addition to the mentioned chemical plants, an industrial park of this nature will attract the installation of other complementary industrial and service activities that benefit from production linkages and economies of scope, such as workshops, industrial warehouses, chemical laboratories, among others.

The physical proximity provided by the hydrogen industrial park also allows for leveraging synergies and economies of scale using shared infrastructure, which may include the shipping port, storage logistics, transport pipelines, industrial water supply, power generation and transmission systems, among others. This enables access to lower costs for associated services. However, the proposal for the green hydrogen industrial park in Mejillones considers that the electricity generation and transmission infrastructure, port, and desalination plant are not directly part of the park but will provide services to the companies located within it.

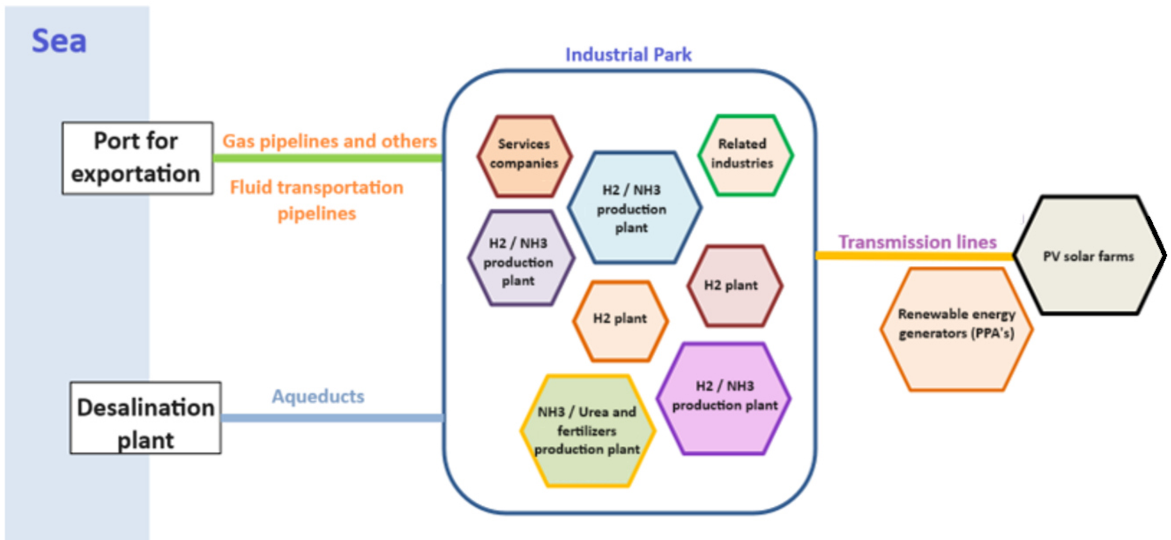

Figure 2. Conceptual framework of H2 Mejillones Industrial Park.

Source: (Self-generated).

In this context, a general business model can be proposed for a project installed within the industrial park, which includes the supply of desalinated or demineralized water, as well as port and storage services, and eventually electrical supply (total or partial), based on service contracts with external providers.

This model would reduce the initial investment costs of the projects (CAPEX), concentrate investments, and focus on the core business, as well as take advantage of lower operating costs (OPEX) based on economies of scale in the provision of those services by specialized companies handling larger volumes, providing their services to multiple clients. It should also be noted that this general business model, based on supply and service contracts, is the basis for the use of shared infrastructure and for leveraging synergies for companies integrating into the industrial park.

In a park like the one presented in Figure 2; other opportunities arise to take advantage of economies of scale. In this regard, industrial processes that by their nature require large production volumes to achieve competitive unit production costs.

This is the case for nitrogen production through air separation and ammonia synthesis using the Haber Bosch process. For this process, production volumes exceeding 2,000 tons/day are required to fully leverage economies of scale in these processes (see also section 5.1.4). To achieve these volumes, hydrogen production as input exceeding 300 tons/day is necessary. For efficient hydrogen production through electrolysis, however, large volumes are not required with current technology. The park design can be based on a set of efficient electrolysis plants of smaller scales feeding into a larger-capacity ammonia production plant.

This production configuration is facilitated if the hydrogen and ammonia plants are located within an industrial park.

1.4 Business model

Figure 3 presents a tolling business model, with a contractual structure for a plant configuration as described. To define these business models and governance, it is necessary to define the system boundaries under evaluation and the stages involved:

- Upstream: All infrastructure related to supplying renewable electricity to the green ammonia production project (blue box in Figure 3) is considered upstream.
- Midstream: All infrastructure related to green ammonia production is considered midstream (green box in Figure 3).
- Downstream: All infrastructure downstream of green ammonia production. The analysis is limited to exporting green ammonia from the port to final consumption.

In the tolling model, the ownership of upstream, production/conditioning, and transportation/exportation belongs to different entities. Conditioning and exportation at the port are not part of the integrated value chain but act as an independent service provider providing these to upstream asset owners.

In this tolling business model, several smaller-scale green hydrogen production plants sell their production to a large-scale green ammonia production plant through long-term *take or pay* contracts. To structure financing for different projects in a model like the one shown in the figure, a contract structure and risk distribution are required that are "bankable" and compatible with *project financing* schemes - under a figure like a Special Purpose Vehicle (SPV), which is a technical and legal challenge.

As shown in Figure 3, there are various types of risks (red box) in the development stages and components of the value chain that must be properly accommodated in the financial models and respective contracts for the entire structure to be viable in obtaining the required financing by participating companies. Applying this model, known as the tolling model, allows for a distribution, diversification, and management of risk among various operators/components of the industrial park, thus delimiting the risk of each project/component individually.

This framework can also help reduce the project's overall risk premium and hence financing costs in the CAPEX stage of each component. This alternative also allows the financial instrument to address the financial transaction as a project portfolio, which can be more attractive.

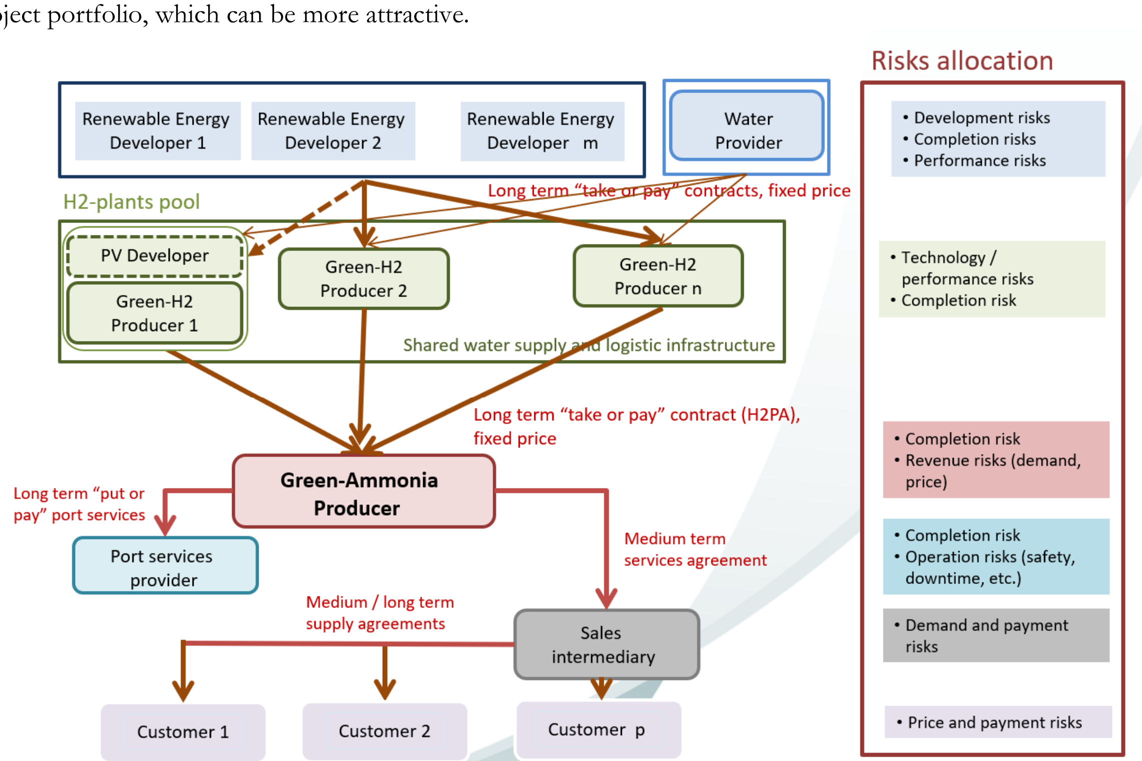

Figure 3. Business model based on supply contracts with multiple suppliers along the value chain.

Source: (Self-generated).

This tolling business model may have variations, which must be duly analyzed according to the specific project needs. DNV 2022 presents the detailed selection criteria for choosing the most appropriate business model for a green ammonia export project. Among the criteria are:

- Promotion of market development and competitiveness.
- Promotion of investment.
- Potential for economies of scale and shared infrastructure.

The way to establish a business model also depends on the level of infrastructure use. As compiled by Inodú in its final report *Analysis of Shared Infrastructure for the H2 Mejillones Industrial Park*.

In addition to economic competitiveness, there are significant advantages from an environmental, territorial, and social perspective. From an environmental standpoint, the planned concentration of industrial plants in a common area avoids territorial fragmentation compared to a distributed and spontaneous location of the same plants. Land use, both for the plants and the infrastructure connecting them to supplies and services, is much more efficient, reducing impacts on various environmental components involved, among others.

From a social and economic standpoint, the development of a planned industrial park can facilitate favorable dynamics of linkages and productive diversification with benefits in job opportunities and quality of life for neighboring communities. These types of benefits will be further addressed in the present report.

Considering the international trade perspective, the production of low-carbon fuels, such as green hydrogen and ammonia, proves advantageous to enter consumer markets with carbon pricing regulations. Carbon markets provide financial incentives to private or public entities for reducing or eliminating GHG emissions. This reduction or elimination is quantified in carbon credits that can be bought or sold (UNDP, 2024). To avoid disadvantaging the European industry, the EU established the CBAM (see section 1.2).

In addition to the above, a recent update to the ETS regulations allows for the temporary granting of free emission allowances to clean fuel generation projects, so starting from 2025, producers of green hydrogen and steel will be able to claim and sell these credits, generating a new source of income, which may promote final investment decisions for the projects.

As of the date of this study, no similar project to the green hydrogen industrial park has been registered in the Voluntary Carbon Markets, so a methodology for accrediting emission reduction in this area has not yet been established. However, initiatives are being developed to create a methodology for accrediting emission reduction within the green hydrogen industry, with the most advanced being the Hydrogen for Net Zero (H2NZ) Initiative H2NZ, CDM NM0381, and the Golden Standard & VERRA, which will be presented in 2025.

Due to the lack of clarity on currently available direct monetization methods, indirect monetization options could be considered, for example, benefiting from the "tax" applied to grey ammonia imports into the EU through the CBAM, or certifying green ammonia with a "low carbon emissions" label to be able to market it as an equivalent in Europe, corresponding to the CO2 price in the EU-ETS (approx. 100 EUR/t CO2e).

For green hydrogen industrial park projects to be eligible for carbon credits, it is necessary to quantify the carbon footprint associated with park services as well as production projects. A preliminary estimate of the carbon footprint of a model green ammonia production plant, with an annual production capacity of 320,000 tons, concludes a reduction of emissions by approximately 600,000 tons CO2eq, compared to its fossil fuel-based production counterpart.

To consolidate the proposal for an industrial park and evaluate the possibility of opting for incentives in international markets, a more detailed analysis of GHG emissions associated with the entire value chain and project dimensions is necessary. Likewise, it is suggested to consider a pilot application of the digital solution to be able to opt for certification of the green hydrogen and derivatives value chain, a tool currently in development through the public-private cooperation project between SAP and GIZ called *Green Proof for the Hydrogen Value Chain – Digital Solutions for Green Hydrogen Certificates*[1]. Finally, it is recommended to monitor the H2NZ initiative and test the application of the methodologies in development for monetization in voluntary carbon markets.

1.5 International experience

There are international cases that illustrate the conceptualization of industrial parks described in the previous section, and their lessons are useful for this work. One example worth highlighting is the Industrial and Port Complex of Pecém (CIPP) in the state of Ceará, Brazil. This Industrial Complex has reserved an area of approximately 1,900 hectares for Power-to-X projects, with an ambitious production target for 2030 of around 1.3 million tons per year of equivalent hydrogen.

The governance of this Industrial Complex is under a public-private consortium, with participation from the State of Ceará and the Port of Rotterdam. To attract investors, a long-term master plan for development was elaborated, offering shared use of infrastructure to projects installed within the park, such as a port terminal, ammonia storage tanks, supply of desalinated water, wastewater treatment, fluid transport pipeline networks, transmission networks, and energy supply, among others.

It is important to note that in the experience of this industrial complex, the importance of considering the forthcoming Green Hydrogen Action Plan is emphasized. This plan serves as a counterpart to Brazil's long-term development master plan, along with the future development of plans and strategies proposed within it. These initiatives will be in effect no later than the year 2030. This information is detailed mostly in the chapter on public policies and the national institutional framework. The following figure summarizes some characteristics of this Industrial Complex:

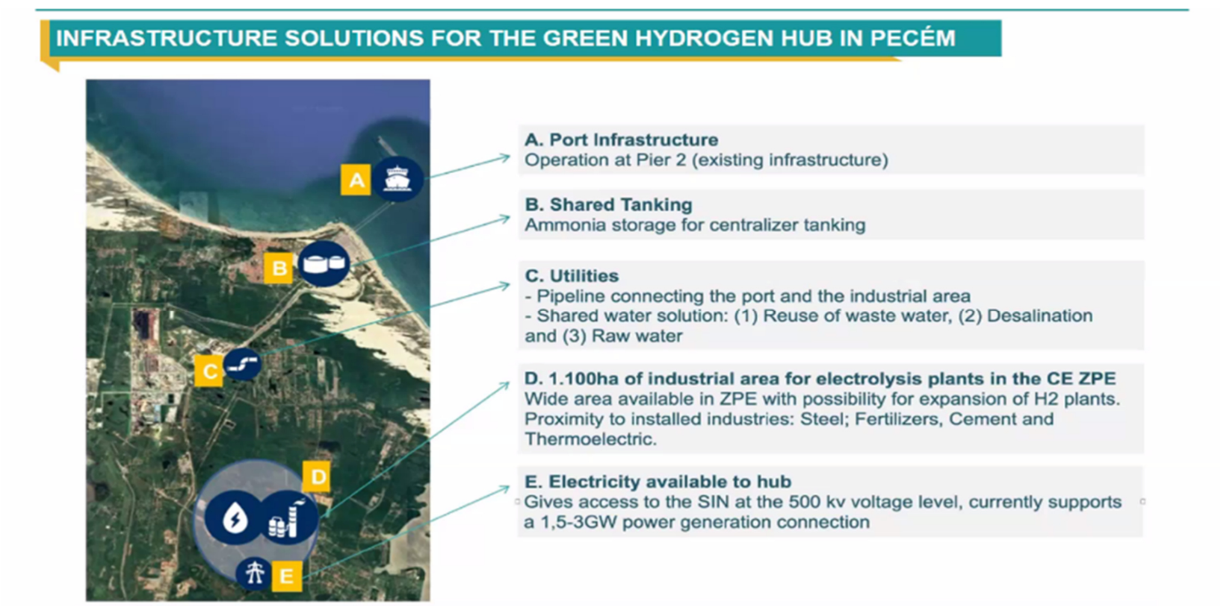

Figure 4. Shared infrastructure at the Complejo Industrial y Portuario in Pécem, Brazil.

Fuente: (CIPP, 2023).

[1] Information available at: https://cdn.leverist.de/prod/7107/h2uppp-ppp-brazil-sap.pdf.

Another interesting case to analyze is the "Point Lisas Industrial Estate" park in Trinidad and Tobago, which is operational. Its objective is the production of grey ammonia and fertilizers, occupying an area close to 1,000 hectares. In this park, multiple companies coexist successfully, taking advantage of benefits from shared infrastructure. Additionally, the distance between the plants within the park does not imply considerable extensions of land, and the industrial park is located near populated areas. Lastly, the park promotes productive chaining, including industries related to fertilizers, explosives, iron, energy generation, logistics, among others.

Figure 5. Point Lisas Industrial State in Trinidad y Tobago.

Fuente: (Hinicio, 2023).

Industrial parks, as evidenced by the case of the "Point Lisas Industrial Estate" in Trinidad and Tobago and the "Pecém Industrial and Port Complex (CIPP)" in the state of Ceará, Brazil, play a crucial role in promoting economic development and industrial efficiency. Their ability to bring multiple companies together in one place, utilizing shared infrastructures and promoting productive chaining, results in a synergy that boosts competitiveness and sustainability of operations. This approach facilitates resource optimization and collaboration among companies, enabling the implementation of more efficient practices and the exploration of new business opportunities.

For the green hydrogen industry, industrial parks offer a conducive environment for integrating the value chain, from renewable energy production to the manufacturing and distribution of technologies related to green hydrogen.

2 Enabling infrastructure in Antofagasta and Mejillones

The Antofagasta region, in northern Chile, stands out as one of the country's most important economic zones, contributing 12% of the national GDP (Statistical Database, 2022). This region is home to a large mining industry, encompassing 63% of the country's entire mining GDP (Statistical Database, 2022). Moreover, Chile is the world's leading copper producer, contributing 25% of global production in 2022 (COCHILCO, 2022), making Antofagasta one of the regions with the highest copper production and exports globally, accounting for 56% of the total copper produced in the country (COCHILCO, 2022).

The most important cities in the region are Antofagasta, the regional capital and home to 63.7% of the population; Calama, near several mines; and Mejillones, a small city located 60 km north of Antofagasta, housing major industries and port facilities.

The development of the mining industry has contributed to the consolidation of regional infrastructure, suppliers of inputs and services industries, as well as the industrial labor market. The Antofagasta region has benefited from the development of human capital, the training of professionals and technicians, and the establishment of universities and research and development centers.

Combining the high renewable potential, the infrastructure scenario is conducive to the development of the new green hydrogen and derivatives industry, which will be reviewed below.

2.1 Renewable energy resources in Antofagasta

Several international studies identify the northern region of Chile as one of the areas with the greatest potential for competitive green hydrogen production, as shown in Figure 6. This potential is mainly based on the incidence of renewable energy procurement costs in green hydrogen production costs.

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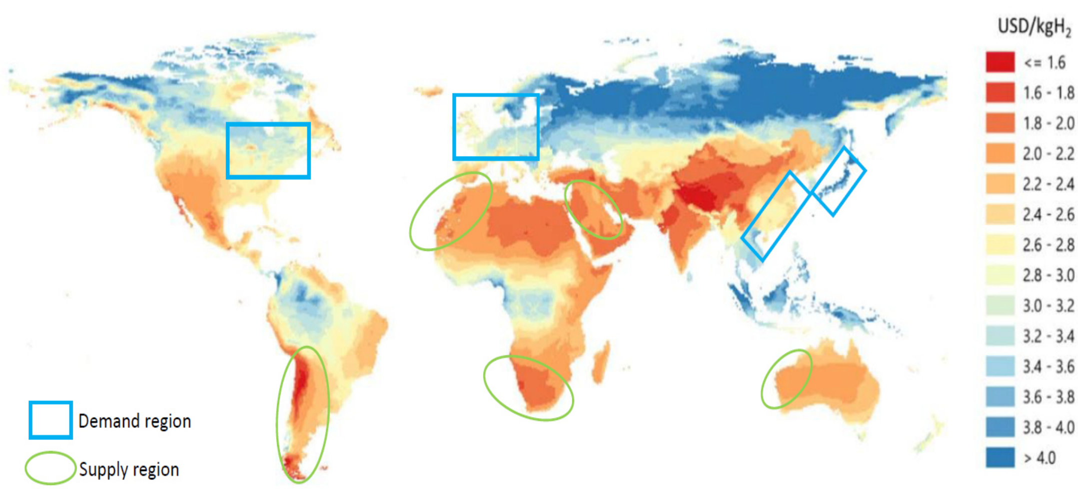


Figure 6. Regions in the world with low-cost green hydrogen production potential.

Source: (IEA, 2019).

The Antofagasta region has a high potential for renewable energy production, with average annual solar irradiation levels, measured as Global Horizontal Irradiation (GHI), of 7 kWh/m2/day in the Atacama Desert as shown in

Figure 7. In areas near the coast, renewable potential decreases. Lastly, the region also features sectors with significant wind potential, with average wind speeds exceeding 6 m/s throughout the year.

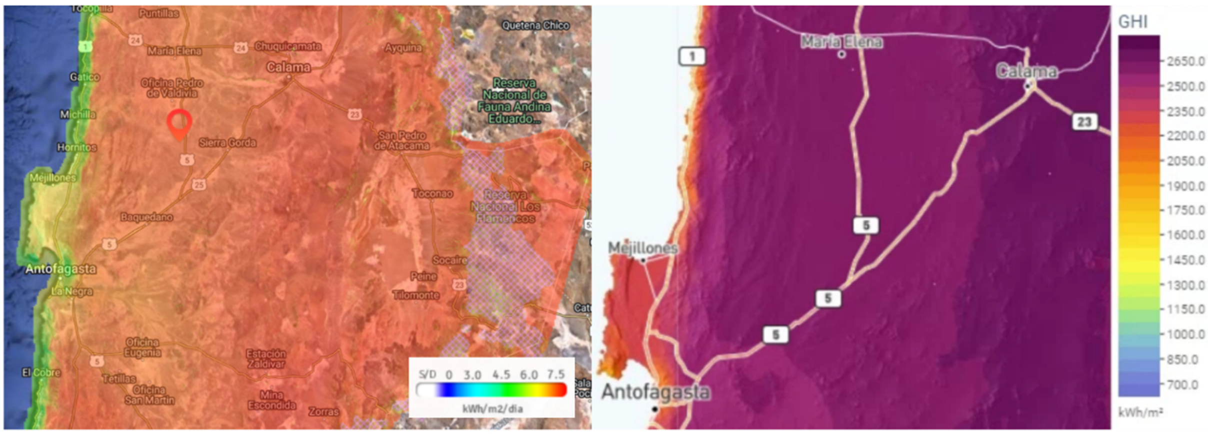


Figure 7. Solar radiation in the Antofagasta region.

Source: (Solar Explorer Ministry of Energy, 2024; and Solargis Platform, 2024).

Given the favorable conditions, there is currently an installed capacity of 4.34 GW of renewable generation in the Antofagasta region, of which 75.8% comes from solar resources and 22% from wind resources (see Table 2 in Annex 2). Additionally, 2.7% of the total installed power corresponds to small and medium-sized plants (less than 10 MW), and 97.3% of the installed capacity corresponds to large-scale plants (greater than 10 MW). Thus, the renewable potential has led to the development of renewable energy projects, also gaining experience in their procurement.

2.2 Regional infrastructure analysis

Green hydrogen and derivatives projects will require different types of infrastructure, especially to facilitate the logistics of these products. The mining industry in Antofagasta has favored the consolidation of regional infrastructure, making it the region with the longest road network in the country (National Road Network, 2023). Additionally, it has a network of railways, gas pipelines, aqueducts, power generation and transmission infrastructure, ports, among others (see Figure 8).

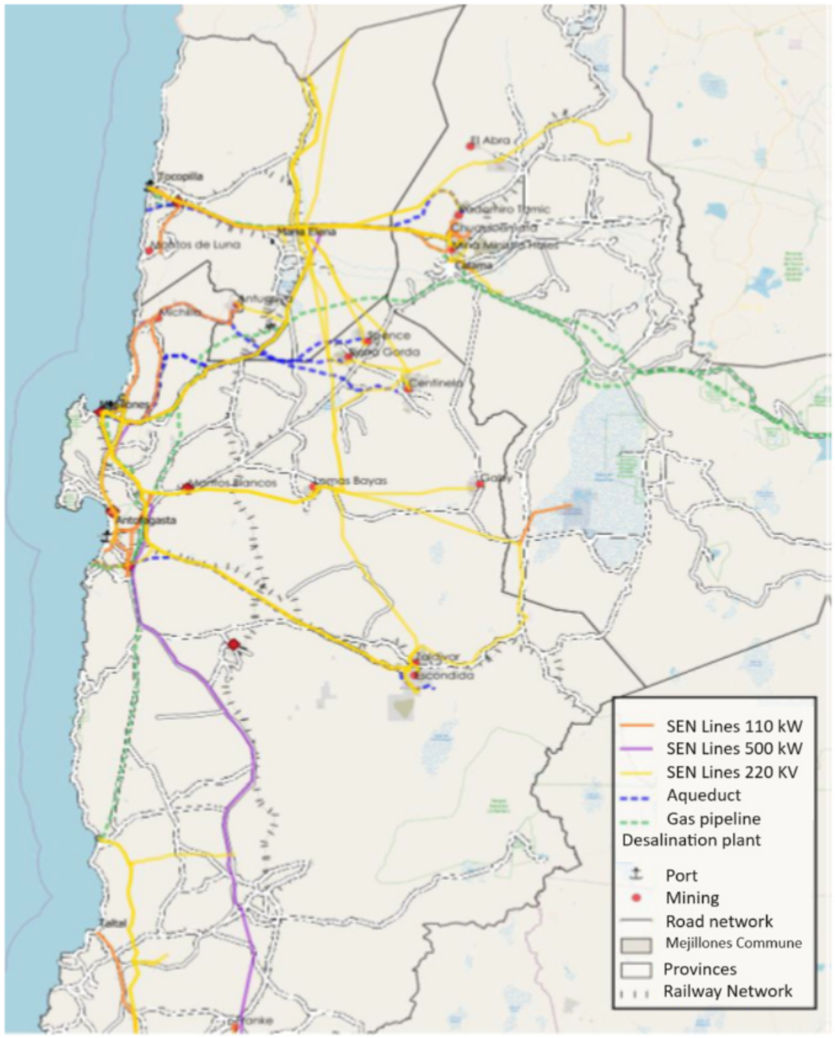


Figure 8. Antofagasta region infrastructure.

Source: (Hinicio, 2023)

Road infrastructure is relevant for transporting resources such as construction materials. The following routes are highlighted: Route 5, the country's main highway; Route 1, connecting the cities of Antofagasta with Mejillones and Tocopilla along the coast; and Route 26, linking Antofagasta with Calama.

Regarding the region's railway lines, they serve various industrial clients, primarily in mining, transporting solid, liquid, bulk, packaged loads, containers, among others. For example, the FERRONOR company's railway crosses from north to south, and the FCAB railway connects Sierra Gorda with the Port of Mejillones, with the latter being an interesting option for transporting green hydrogen and/or its derivatives to mining operations for subsequent use.

Additionally, the regional infrastructure includes three natural gas pipeline networks: Atacama Gas Pipeline, Norandino Gas Pipeline, and Taltal Gas Pipeline. The technical characteristics of these are summarized in Annex 2, Table 3. Particularly, the sections associated with the Taltal Gas Pipeline have potential for partial injection of green hydrogen through pipeline reconditioning methods.

Regarding regional electrical infrastructure, Antofagasta has several lines of the National Electric System (SEN), forming an interconnected network with different voltage levels. Since electricity is crucial for hydrogen production, Section 2.3: Renewable Energy Supply and Transmission Networks provides a deeper analysis of electrical infrastructure and its potential to supply renewable energy.

The region has multiple ports and port terminals in the municipalities of Mejillones, Antofagasta, and Tocopilla, offering options for exporting green hydrogen and/or its derivatives. The location of Mejillones Bay provides convenient access to global maritime routes, with terminals that are particularly suitable for the new green hydrogen industry in the region. Given that proximity to the coast and port terminals is a key criterion for selecting locations for hydrogen and derivative projects, the analysis of associated infrastructure is further explored in Section 2.4: Logistics and Transportation Infrastructure in Mejillones.

Moreover, Antofagasta has multiple desalination plants and aqueduct networks. Currently, the region has a seawater desalination capacity of approximately 6600 l/s. The treated water is mainly consumed by the copper production industry; however, industrial water demand (2.5% of the region's production) is primarily due to thermoelectric power plants, such as those in Mejillones. Section 2.5: Industrial Water Supply provides further details on the region's production capacity and its potential to supply the hydrogen industry.

While it is concluded that the Antofagasta region has enabling and developed infrastructure, a thorough analysis of the requirements of the main components of the green hydrogen value chain, their locations, as well as existing infrastructure, is needed to design the optimal configuration of a plant and additional required infrastructure.

The following sections provide a deeper analysis of electrical, port, and water infrastructure to meet the needs of a green hydrogen and ammonia industrial park. Finally, the chapter concludes with a review of potential locations for the components of the value chain for the industrial park.

2.3 Renewable energy supply and transmission networks

The Antofagasta region has an electrical transmission network infrastructure and substations suitable to meet the current requirements of the regional industry and population centers (see Figure 9).

The existing electrical infrastructure also connects to Mejillones. The area is currently a major generation hub with over 3.4 GW of installed capacity, associated with 9 thermoelectric generation plants (National Electric Coordinator, 2024). However, the national electric grid decarbonization plan includes a progressive disconnection agenda for coal-fired power plants (see Annex 2, Table 2). This transition will pose challenges and opportunities for the conversion of generation and transmission infrastructure in Mejillones, potentially enabling opportunities for the green hydrogen industry.

Furthermore, Mejillones has two major national electrical substations: the Los Changos trunk substation at 500 kV/220 kV, with an approximate capacity of 2700 kVA, and the SE Kapatur 220 kV substation, with an approximate capacity of 1600 kVA.[2]

[2] Information available at: https://infotecnica.coordinador.cl/instalaciones/subestaciones

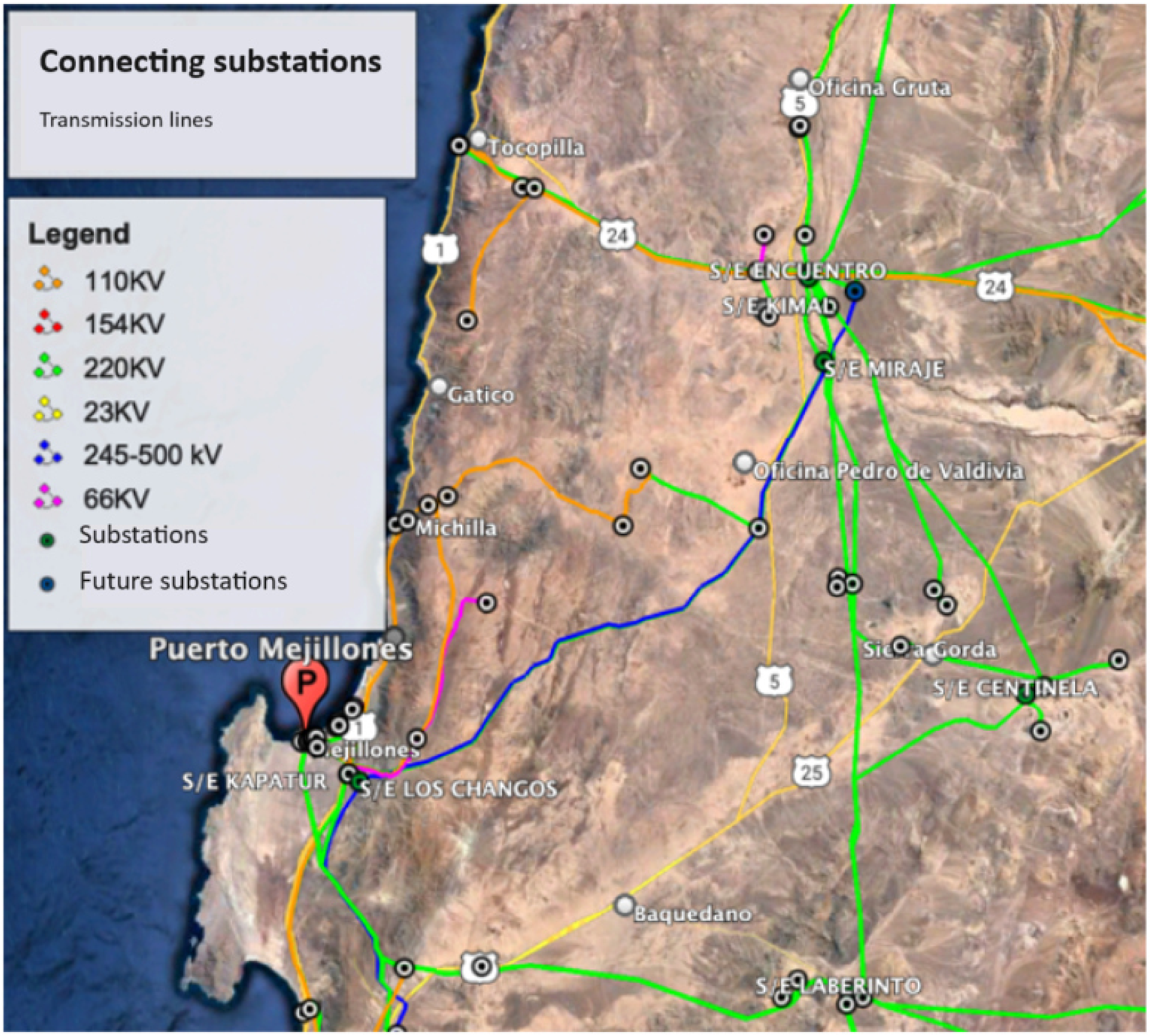


Figure 9. Electric transmission networks and substations in Antofagasta.

Source: (Suazo, 2022).

Initially, the electrical infrastructure, which is part of the National Electric System, is available to provide services to the generation and consumption plants of projects in the new green hydrogen industry, depending on the available capacity of the relevant sections. However, today, systemic costs for using the electrical infrastructure are high, reaching projected costs of 10 to 16 USD/MWh by 2031 (H2 Chile, 2023). These costs significantly increase, by 60% or more, the electricity supply costs for electrolysis plants, reducing the competitiveness of levelized costs of green hydrogen production (LCOH), for which electricity cost is the main component.

Due to the high costs and large volumes of energy to transmit, the green hydrogen projects announced for installation in Antofagasta are considering building dedicated transmission systems (off-grid). These systems will play a relevant role in the industry's development in the region and must be properly considered in territorial planning.

Based on these challenges, this study evaluated alternatives for transmission systems and possibilities of shared use of dedicated lines to meet the requirements of an industrial park for green hydrogen and derivatives (Inodú, 2023). Four transmission system alternatives were considered (see Figure 10), with different capacities and voltage levels, designed to meet the requirements of a green hydrogen and ammonia plant. Each alternative considers the possibility of implementing the project in two stages, scaling from 800 MW to 1600 MW.

- **Alternative 1:** Proposes, in stage one, transmitting through a 220 kV line, reaching this voltage level at the high-voltage yard of the hydrogen plant, where the voltage is reduced using a 220/33 kV transformer to power the electrolyzers and the rest of the plant. For stage two, this option proposes investing in a second 220 kV line.

- **Alternative 2:** Proposes the construction of a 500 kV transmission line, energized at 220 kV in a first stage, reaching this voltage level at the high-voltage yard of the plant.

- **Alternative 3:** Proposes the construction of a 500 kV transmission line, initially energized at 500 kV, and feeding this voltage level to the high-voltage yard of the hydrogen plant, where the voltage is reduced using a 500/33 kV transformer to power the plant.

- **Alternative 4:** Proposes the construction of a 500 kV transmission line, initially energized at 500 kV, and a reducing substation to transform from 500 kV to 220 kV to power the high-voltage yard of the plant with 220 kV.

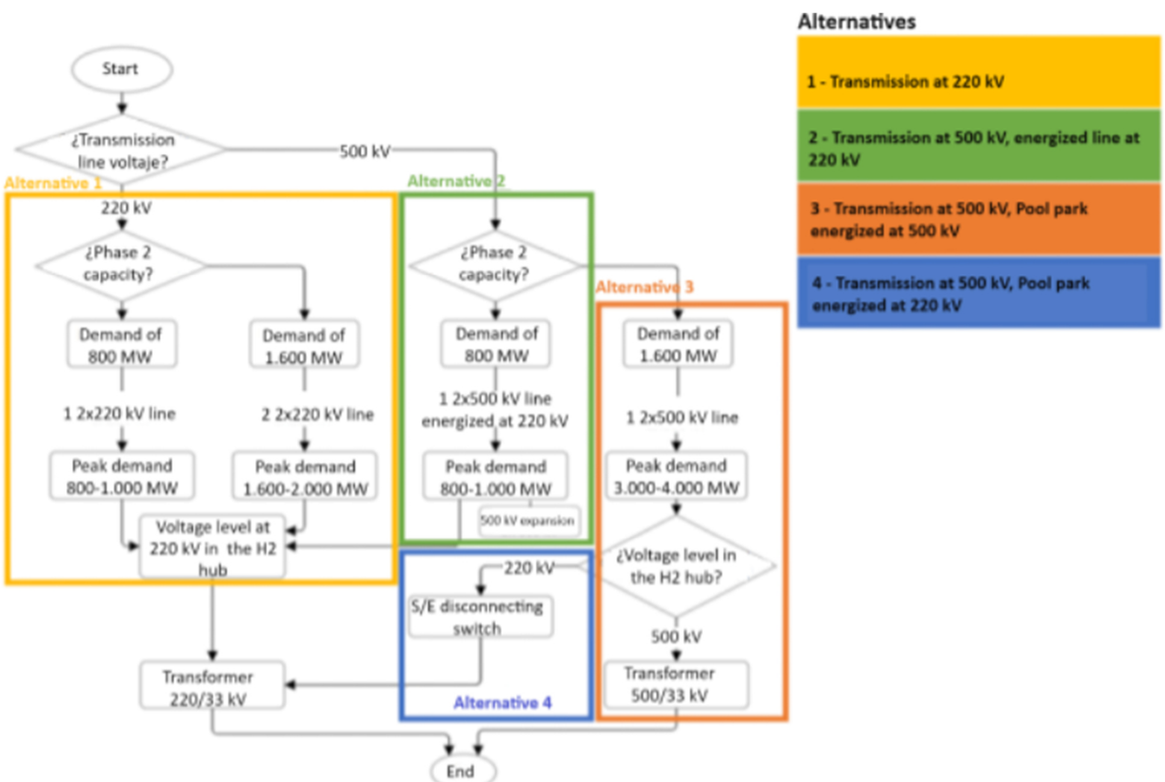


Figure 10. Considered configurations.

Source: (Inodú, 2023).

For each alternative depicted in the previous figure, an estimate of investment and operating costs was made to evaluate their efficiency and flexibility in addressing different demand scenarios for projects and an industrial park (see Figure 11). Regarding Figure 11, it is worth noting that the left graph presents the investment cost ranges of each alternative for the first stage, along with the corresponding transmission capacity. The right graph presents the total costs considering both stages.

This preliminary evaluation allows us to conclude that Alternative 1, with 220 kV transmission lines, would be the most economical to meet the requirements of a project with a maximum electrolysis capacity of up to 2,000 MW. A two-circuit 220 kV line has a maximum transmission capacity of 1,000 MW. Therefore, to increase the transmission capacity to achieve an electrolyzer capacity of 1,600 to 2,000 MW, it would be necessary to build another parallel line with the same characteristics.

On the other hand, Alternative 3 consists of a double-circuit line at a voltage level of 500 kV, with much higher capacity, between 3,000 MW and 4,000 MW. Analyzing the second scenario, which characterizes a project with a demand of 1,600 MW, this option turns out to be 44M USD more expensive (according to maximum cost) than the first alternative.

However, Alternative 3 may be convenient by using space more efficiently and transmitting enough energy to Mejillones for two projects with up to 2,000 MW of electrolysis capacity. The alternative would also be more suitable for meeting the requirements of an industrial park, taking advantage of shared infrastructure, and distributing installation costs among several projects. It should be noted that this will depend on the possibility of coordinating project requirements over time with an appropriate business model.

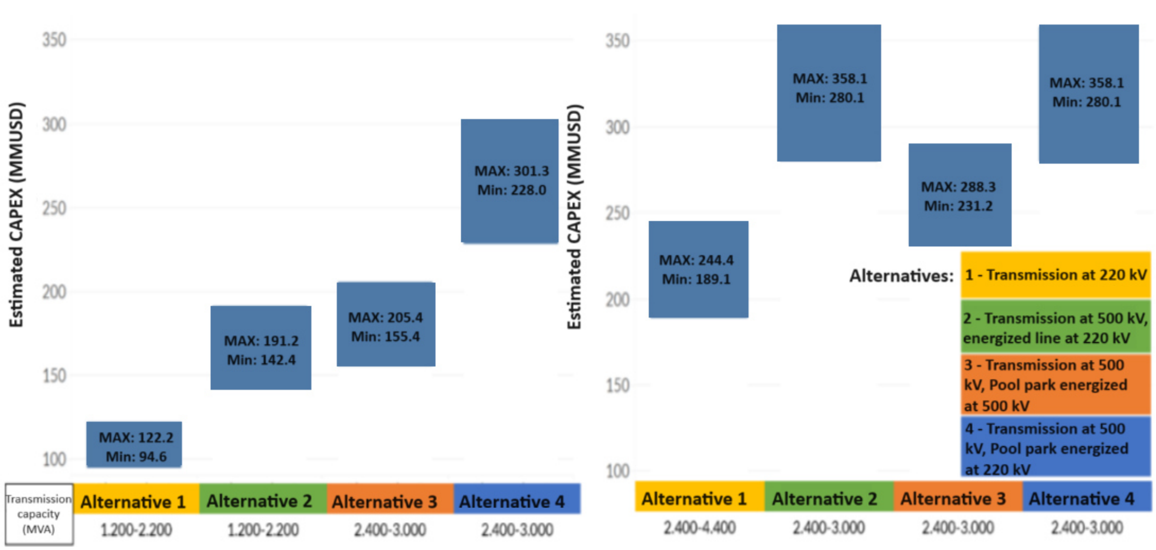


Figure 11. Investment cost of the 4 alternative transmission system options.

Source: (Inodú, 2023).

Based on the alternatives studied, options for transmission system configuration or architecture to supply a green hydrogen industrial park were analyzed (see Figure 12). The installation of dedicated 500 kV lines for large capacity projects (2,800 MW of electrolysis) and shared lines for two lower capacity projects (1,400 MW of electrolysis) is proposed.

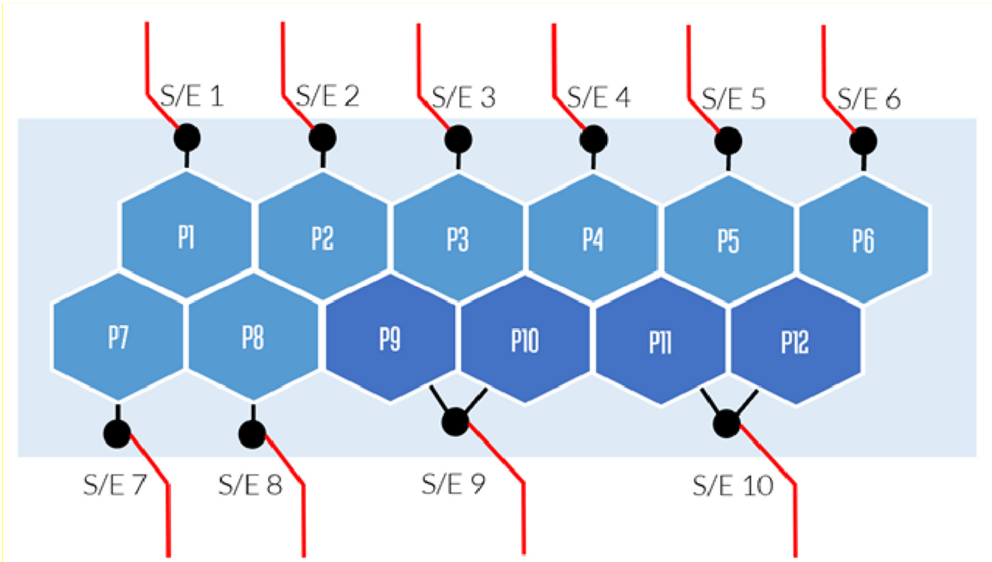


Figure 12. Architecture of the 500 kV electric power transmission system for an industrial park.

Source: (Inodú, 2023).

In conclusion, a green hydrogen industrial park will require several transmission lines due to the large volume of energy required for green hydrogen production and the potential different locations of renewable energy generation plants.

Additionally, the possible growth of the park will require the construction of transmission lines in stages. This poses a challenge for territorial planning, for example, by defining corridors[3] to avoid territory fragmentation due to this infrastructure, and, on the other hand, imposing limits on the number of green hydrogen projects that can be installed in the park.

2.4 Logistic infrastructure and transportation in Mejillones

The Antofagasta region has port infrastructure in the municipalities of Mejillones, Antofagasta, and Tocopilla. Mejillones Bay has proven to be the main maritime solution for large-scale mining in Chile due to its proximity and connectivity. It has over 20 years of development, handling different types of cargo: breakbulk, containers, projects, solid and liquid bulk, among others. Furthermore, connectivity and proximity to water supplies, electrical substations, and energy projects are key strategic criteria for the installation decision of industries from other sectors.

Mejillones' port infrastructure, and industrial synergy, is interesting for the development of an industrial park that promotes energy transition through the production of green hydrogen and derivatives. To assess the potential, this section analyzes the existing infrastructure and the required infrastructure to provide services to green hydrogen and derivatives projects that are installed in the described industrial park.

In the municipality of Mejillones, there are currently 11 port terminals that provide services to different clients and industrial products in the Antofagasta region (see Table 1):

Name	Products	Relevant Products	Use	Operation	Owner

[3] In this context, *corridor* refers to a strip of land that houses two or more parallel transmission lines, connecting power generation plants with electricity consumption centers, allowing for a more efficient use of the territory.

Enaex	Liquid bulk	Anhydrous ammonia	Private Use	Owner-operated	Enaex
Oxiquim	Liquid bulk	GLP	Private Use	Owner-operated	Oxiquim
Puerto Mejillones	Solid and liquid bulk commodities	Coal, sulfuric acid, mineral concentrates, clinker	Private and Public Use	Owner-operated	Puerto Mejillones SA
Puerto Andino	Solid bulk commodities	Coal	Private Use	Owner-operated	Puerto Mejillones SA
Terquim	Liquid bulk	Sulfuric acid, chemicals, and fuels	Private Use	Owner-operated	ODFJELL Group
lnteracid	Liquid bulk	Sulfuric Acid	Private Use	Owner-operated	lnteracid Trading
Puerto Angamos	Containers, general cargo, breakbulk, solid bulk	Metallic copper, Copper concentrate, Fertilizers, others	Public Use	Mejillones Port Company	Complejo Portuario Mejillones
Terminal Graneles del Norte (TGN)	Solid bulk	Coal	Private and Public Use	Operated by TGN	Complejo Portuario Mejillones
GNL Mejillones	Liquid bulk	GNL	Private Use	Owner-operated	Engie Chile, GNL Ameris IPM SpA
Terminal Michilla	Solid and liquid bulk commodities	Copper concentrate, sulfuric acid	Private Use	Owner-operated	Antofagasta Minerals S.A (AMSA)
Terminal Esperanza	Solid bulk	Copper concentrates	Private Use	Owner-operated	Agental Ltda.

Table 1. Port terminals in the municipality of Mejillones.

Source: (Hinicio, 2023).

Of the mentioned terminals, those belonging to the Mejillones Port Complex (CPM)[4] have characteristics particularly suitable for providing logistical services to the future hydrogen industrial park. CPM is a subsidiary of CODELCO[5], which serves as the owner and port authority of the terminals located on its premises. By design, it is an industrial port for public use, guaranteeing open access on non-discriminatory terms to all potential users. The port has around 200 hectares of its own land, and a master plan for its long-term planned development, based on a concession model that allows private investment and operation of its terminals.

The Port Complex is multipurpose and currently has two terminals (see Figure 13), Terminal 1 (also known as Puerto Angamos) for general cargo and containers, and the North Bulk Terminal (TGN) that handles solid bulk cargo. The latter currently unloads coal; however, starting in the second half of 2024, it will also handle the shipment of copper concentrates.

[4] More information available at: https://mejillones.com/es/sobre-nosotros/#modelo-de-desarrollo

[5] CODELCO, "Corporación Chilena del Cobre" in spanish, the Chilean State-owned Copper Corporation, is the largest copper producer globally, with a production of refined copper totaling 1,324,554 tons in the year 2023.

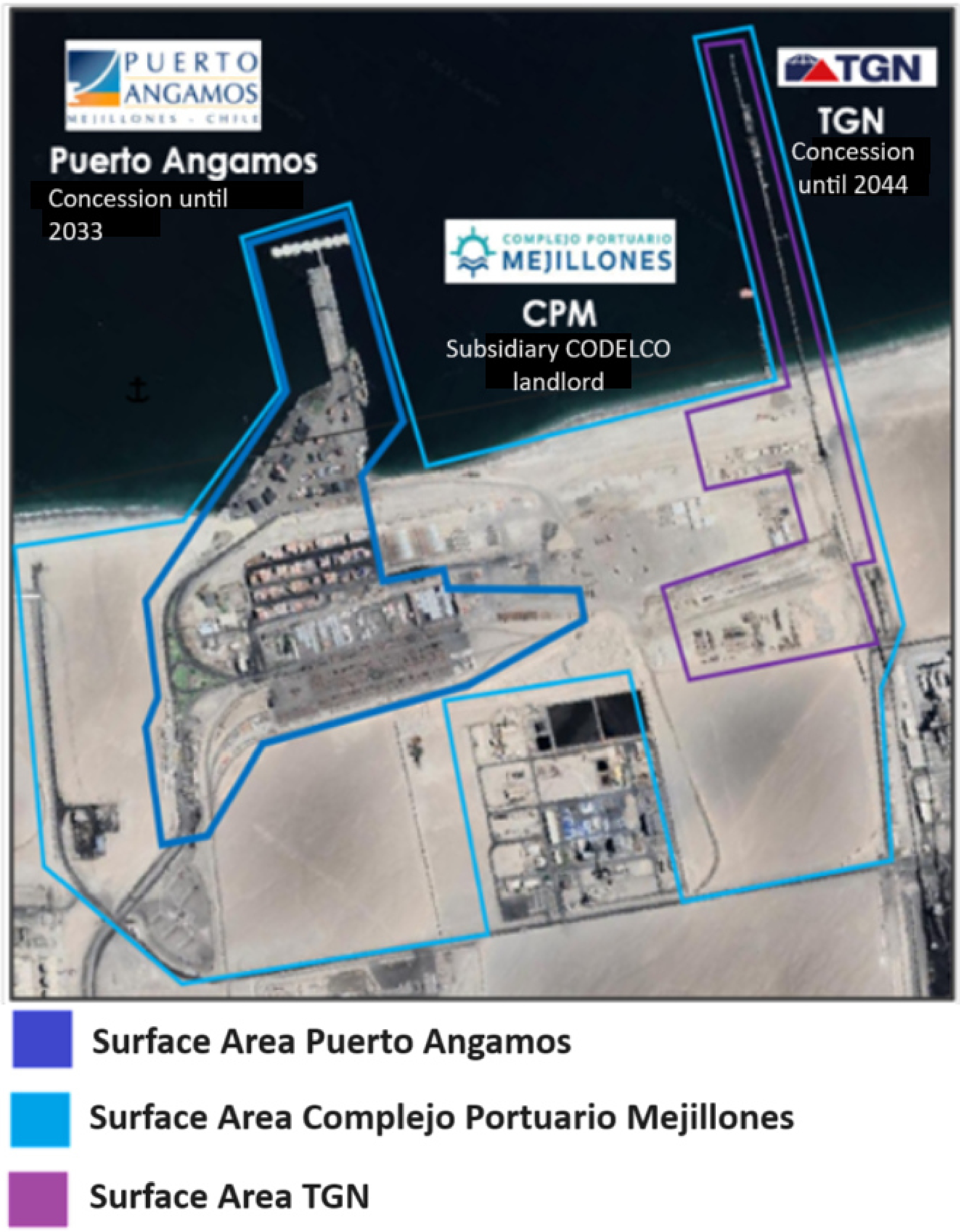


Figure 13. Terminals of the Port Complex of Mejillones.

Source: (Self-generated based on information from Mejillones Port Complex S.A.)

The Angamos Port or Terminal 1, operated by Compañía Portuaria Mejillones S.A. (a consortium formed by the companies Belfi and Ultramar), has 4 berths, allowing two berths together to handle the largest vessels on the west coast of South America. The terminal has a maximum capacity of approximately 4,5 million tons annually of general cargo and an available capacity of approximately 1 million tons in containers.

Due to its characteristics, it is the terminal intended to handle the cargo of industrial and energy projects developed in the region (machinery, industrial equipment, parts, and materials, etc.). This is how, between 2022 and 2023, the terminal operated for the components of Chile's and Latin America's largest wind farm, the Horizonte project, handling 140 wind turbines and 79-meter-long blades.

On the other hand, the TGN Terminal, also operated by Compañía Portuaria Mejillones S.A., currently has one berth. However, the expansion project will enable the provision of an additional loading berth for copper concentrate. TGN has a total cargo transfer capacity of approximately 3.05 million tons annually and an unloading capacity of 17,000 ton/day. Currently, this terminal is used for coal unloading for the Angamos and Cochrane Power Plants.

To meet future export requirements for ammonia, the Port Complex is considering two alternatives: (1) adapting a berth at the TGN or (2) developing a new liquid bulk terminal. Regarding the first alternative, TGN currently has operational availability for the transfer of additional cargo.

Furthermore, due to national decarbonization plans, the disconnection of the Angamos power plant is expected in the medium term (announced for 2029) (see Table 2 in Annex 2), projecting that the terminal will generate increased port availability in the coming years. It is estimated that the ammonia opportunities at TGN reach a maximum site capacity of approximately 7 million tons of ammonia per year.

Additionally, the terminal has a storage capacity of 100,000 m3 (Hinicio, 202312), with tank placement in areas with capacity for expansion. Therefore, the current and projected availability of existing infrastructure is timely for ammonia loading and eventually other liquid bulk cargoes, as shown in Figure 14, which will reduce the required investments for project development and the timelines involved in enabling berths with the necessary characteristics.

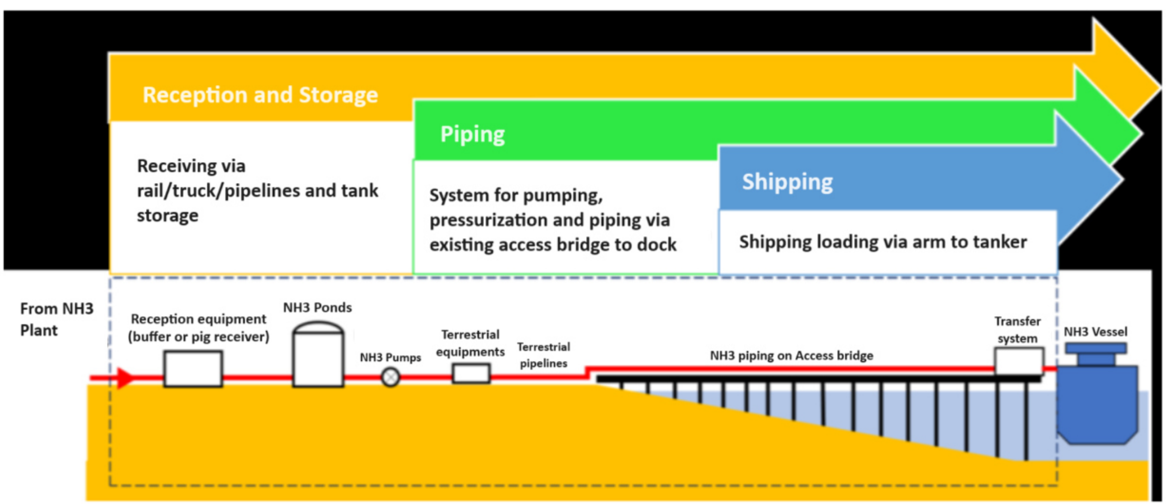


Figure 14. Scheme of ammonia loading terminal at TGN.

Source: (Terminal de Graneles Norte, 2023).

The second alternative is to develop and build a new liquid bulk terminal at the location outlined in the Port Complex master plan (see Figure 15). This alternative would require the Port Complex to carry out a bidding process for private investors to finance, build, and operate the new terminal, under the concession scheme used by the Port Complex. On one hand, the advantage of this alternative is the development of a specialized terminal for liquid bulk cargoes, with significant long-term growth capacity, and tailored to meet the requirements of the green hydrogen industry and its derivatives.

On the other hand, the disadvantage of the alternative is that it requires more investment and development timelines. It is expected that the Port Complex will define the alternative, considering timelines compatible with the project developers' requirements, to consolidate its position as the main port for the hydrogen industry in Antofagasta.

Figure 15. Master plan of Complejo Portuario Mejillones.

Source: (Mejillones Port Complex). [6]

2.5 Industrial water supply

The Antofagasta region has multiple desalination plants and aqueduct networks, which transport desalinated water to mining and industrial facilities (see Figure 1, Annex 3). Currently, the region has a seawater desalination capacity of 6,603 l/s (see Table 1, Annex 3), representing approximately 77% of the national capacity. Additionally, there is an expected capacity growth to reach 19,591 l/s, considering the projects and expansions announced to date, such as the CRAMSA project with a capacity of 8,000 l/s that entered the Environmental Impact Assessment Service (SEIA) in 2022 (Hinicio, 2023).

The desalinated water is mainly used for copper production, accounting for approximately 65% of consumption, followed by drinking water production (17%) and industrial water (2.5%), mostly in thermoelectric plants. Due to decarbonization plans, thermoelectric plants are expected to cease operation and thus their water consumption. On one hand, the seawater intake infrastructure to supply cooling systems for thermoelectric plants can be repurposed to supply desalination plants. On the other hand, since some power plants have desalination plants, there is an opportunity to repurpose desalination infrastructure and its aqueducts for new purposes. For example, Mejillones has an installed seawater desalination capacity of 1,120.1 l/s (see Table 1, Annex 3). Of these, 112 l/s will be made available after the shutdown of the Cochrane and Angamos power plants.

[6] Information available at: *https://mejillones.com/es/sobre-nosotros/#modelo-de-desarrollo*).

Considering the availability of existing water infrastructure and its synergies with the needs for hydrogen production, it is possible to evaluate the opportunity to share or enable seawater treatment and transport infrastructure. This assessment is also relevant due to the long permit acquisition times, which can exceed the norm, specifically for maritime concessions.

In this regard, according to a study by the Chilean National Commission for Evaluation and Productivity, the average actual time it takes to obtain a maritime concession permit is 34 months, while the legal deadline is 6 months, the difference is due to the extended permit issuance period and the high number of pending applications (CNEP, 2023). Therefore, existing water infrastructure has the advantage of reducing development time, which is opportune for commercializing the treatment volumes of desalination plants from thermoelectric plants that will be phased out.

The present report includes a technical-economic analysis of two seawater treatment plant scenarios, with production capacities of 50 l/s and 500 l/s, respectively (see Annex 3). From this, it is concluded that individual green hydrogen and derivative projects can be economically benefited in an industrial park due to reduced investment and operating costs. Due to the high potential for renewable energy in the Antofagasta region, energy costs will be lower and will enhance this benefit.

ID	NAME	STATE	CLIENT	CAPACITY (l/s)	USE
1	Minera Sierra Gorda	Operative	KGHM International	63	Copper
2	Distrito Centinela (Esperanza + El Tesoro)	Operative	Antofagasta Minerals	50	Copper
3	Mantos de la Luna	Operative	Minera Mantos de la Luna	20	Copper
4	Moly-Cop	Operative	-	4.3	Steel
5	Taltal	Operative	EPM	5	Drinking Water
6	Michilla	Operative	Halderman Mining Company S.A.	70	Copper
7	Angamos	Operative	AES Andes	56	Industrial
8	Spence Growth Option	Operative	BHP	1,000	Copper
9	EWS y EWSE	Operative	Minera Escondida	3,858	Copper
10	Desaladora Tocopilla	Operative	EPM	75	Drinking water
11	Desaladora Norte Antofagasta	Operative	EPM	1,053	Drinking water
12	Mejillones Planta Hornitos	Operative	Caja Compensación Los Andes	4.34	Drinking water
13	Norgener	Operative	AEs Andes	25	Industrial
14	CTT Tocopilla	Operative	ENGIE	22	Industrial
15	Minera Antucoya	Operative	AMSA	30	Copper
16	EE Cochrane	Operative	AES Andes	56	Industrial

Table 2. Installed Desalination Capacity in Antofagasta in Operation.

Source: (Vicuña & et al, 2022).

N.B. The mapped projects account for approximately 97% of the total in the Antofagasta region. Antofagasta.

2.6 Potential locations of value chain components

Regarding potential locations, there are several possible configurations for the spatial disposition of the main components of the green ammonia value chain, renewable electricity generation plants, hydrogen and ammonia production chemical plants, and desalinated water production plant. Each configuration has different infrastructure requirements for transporting energy and products from their origin to the transformation centers and destination of production.

A first conclusion from the analysis of regional resources and infrastructure is that electricity generation plants should be in areas with the best renewable resources, given the critical impact of electricity production costs on the total production cost of green hydrogen.

This leads to seeking locations in the interior sectors of the Atacama Desert, where solar irradiation conditions are optimal. The relative ease and efficiency of electricity transport from production areas to consumption areas, the possibility of building dedicated power lines or using existing electrical networks and power plants complementarily allow selecting locations for chemical plants with greater flexibility, leveraging other location advantages.

In the case of hydrogen production, it is convenient to locate the plant near the water supply plant. It is more efficient for the ammonia plant to be located near the hydrogen plant and near the port if its production is mainly for export. This configuration simplifies logistics and reduces risks and costs of investment and operation of fluid transport infrastructure (water, hydrogen, ammonia). A very relevant advantage of this configuration is that it allows the formation of an industrial chemical hub, where chemical plants of several companies can be in an industrial park.

Regarding the transport of ammonia over short distances (less than 15 km), for example, from an industrial park to the port area, it was determined that the economically most efficient alternative is to transport ammonia as cryogenic liquid at ambient pressure through pipelines.

Regarding storage, and from the perspective of economies of scale and synergy, the most efficient option would be to store ammonia in large tanks located within the port area. According to current health regulations (Circular B32 from the Ministry of Health), the maximum allowed value for ammonia storage in surface tanks (to classify it as disturbing) is 40,000 m3. For the considered volumes, ammonia storage as cryogenic liquid at -33°C and 1 atm is contemplated, which is the standard for maritime transport, minimizing infrastructure and land requirements. Therefore, based on the selected storage conditions, the limit to store is approximately 27,000 tons of ammonia.

Based on these considerations, different strategic locations are proposed for the renewable energy generation park and the ammonia industrial park (see Figure 16 for reference locations). The selected configuration involves using power transmission lines for renewable electricity.

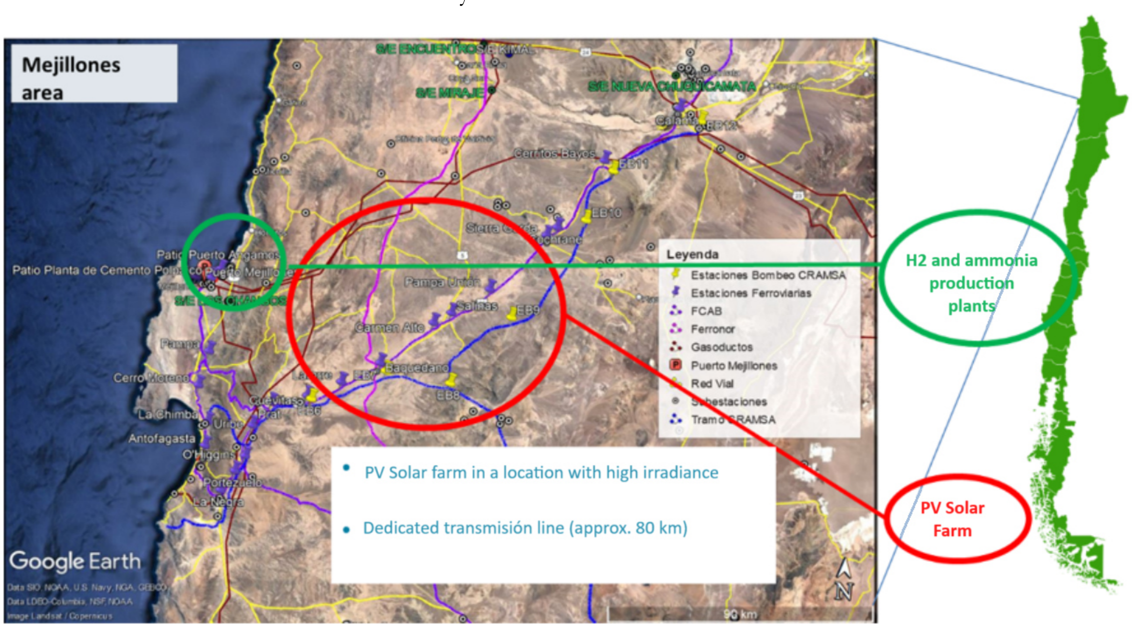


Figure 16. Locations of the main plants in the production system.

Source: (Self-generated).

3 Master plan for the development of an industrial plan in Mejillones

The master plan presented in this chapter corresponds to a long-term vision, up to the year 2050, for the development of a potential industrial park in Mejillones. Its purpose is to support the reservation of land that makes planned development viable, and it can be used as a reference instrument for territorial planning. The plan will help create favorable conditions for industrial development in the long term, facilitating collaboration between public and private actors, shared use of infrastructure, and leveraging synergies while minimizing negative environmental impacts, among other multiple advantages.

The sizing of the surface presented here is based on assumptions and plausible projections for the stated purpose, and it is not intended to be a rigorous estimate of future parameter values. As it is an emerging industry, there is uncertainty about its future evolution, so precise projections of these parameters are not attempted. What can be stated with certainty is that if strategic land reservation for future growth is not made possible, the planned development of a park will be unfeasible.

In that context, sizing of reserve areas, combined with preliminary planning of necessary common infrastructure and an examination of territorial limitations, will enable the presentation of viable location options for the industrial park in the Mejillones area.

3.1 Preliminary area sizing

Based on the specific study conducted for this project (Hinicio 2023, H2 Industrial Park Mejillones), it is projected that domestic demand in the Antofagasta region will mainly be for hydrogen, with around 327 ktpa H2 by 2040 and 437 ktpa H2 by 2050. In the case of export demand, this will mainly be for ammonia, with 537 ktpa of H2 equivalent by 2040 and 1,138 ktpa H2 equivalent by 2050, approximately. By 2050, the total demand for hydrogen and derivatives in the region is expected to correspond to 2.65 Mtpa H2 equivalent. The estimated demands mentioned are graphed below:

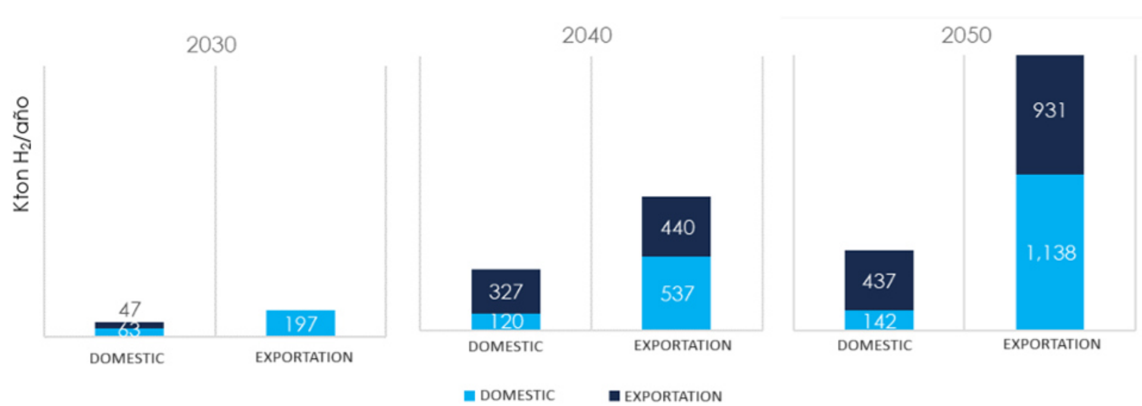


Figure 17. Demand of H2 and NH3 in the Antofagasta region.

Source: (Hinicio, 2023).

Demand	Unit	Domestic Consume	Export	Total
Hydrogen	kpta H2	437	931	1,368
Ammoniac	kpta H2 Equivalent	142	1,139	1,281
Total	kpta H2 Equivalent	579	2,070	2,649

Table 3. Hydrogen and its derivatives demand projection for the Antofagasta region.
Source: (Hinicio, 2023).

For the sizing of the industrial park, two types of projects were considered: type 1 (see Figure 18) with 100% of its generation from solar energy, and type 2 (see Figure 19) with 70% of its generation from solar energy and the remaining 30% from wind energy. Additionally, it was considered that the production of the industrial park in this time horizon would supply the entire demand of the region (2.65 Mtpa of hydrogen equivalent), both for local consumption and for export, requiring 28.3 GW of electrolysis.

This assumption is also considered as an optimistic scenario, contemplating that the park could accommodate other plants producing indirect derivatives and other services in the future, benefiting from the infrastructure and synergies of the park. Thus, the sizing is done according to the equivalent of the maximum total potential that the industrial park could host.

The main assumptions considered to estimate the maximum productive potential of the project are as follows:

- Export will mainly be renewable ammonia, while the remaining hydrogen is assumed to be exported through its derivatives according to market evolution, such as methanol and SAF (*Sustainable Aviation Fuel*).
- Ammonia and other H2 derivatives will be exported using the facilities of the Mejillones Port Complex.
- Storage of export products will be located at the port to optimize logistics, while plants will have H2 and NH3 storage as buffers and for domestic consumption.
- Hydrogen and ammonia for local consumption will be transported via land, by railway or pipelines, whichever is deemed more efficient, for consumption by nearby industries and the mining sector of the region.

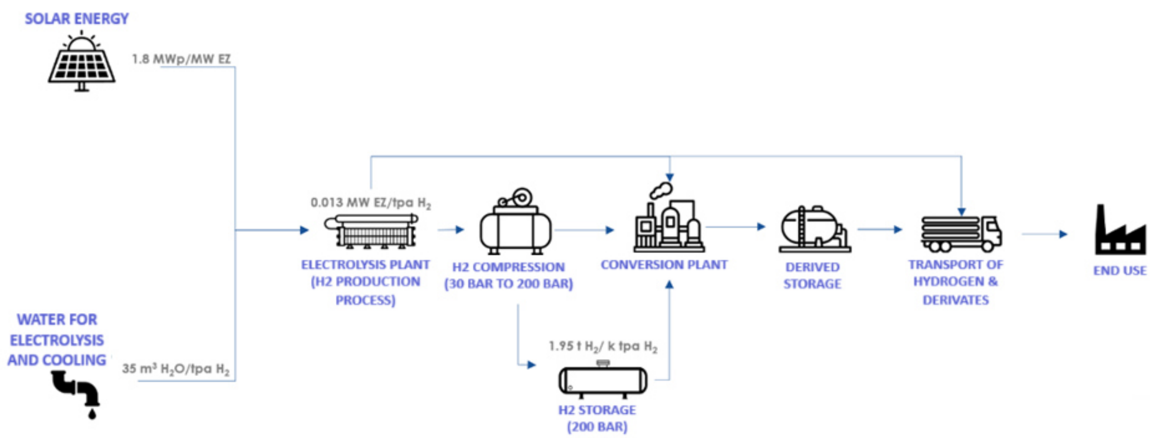


Figure 18. Scheme of a type 1 project based on solar energy.

Source: (Hinicio, 2023).

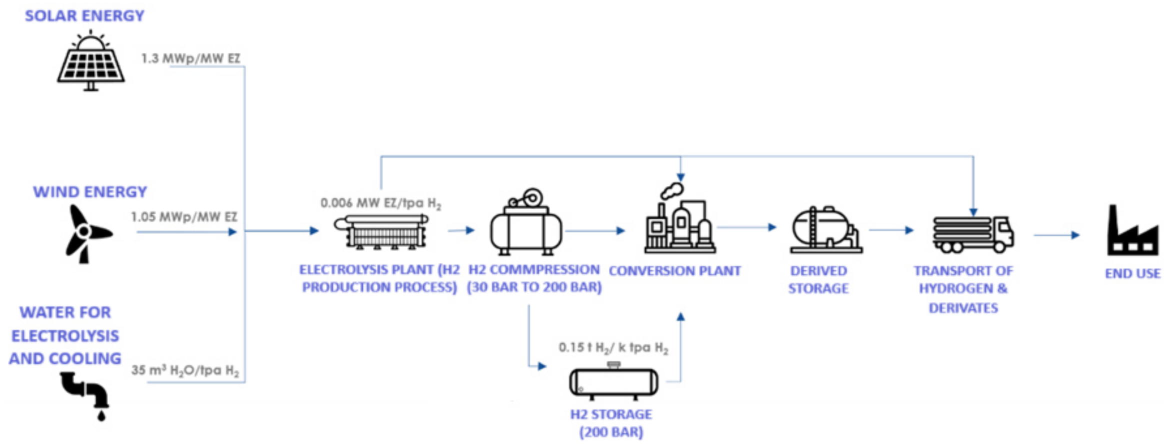


Figure 19. Scheme of a type 2 project based on solar and wind energy.

Source: (Hinicio, 2023).

The detail of hydrogen and derivative production from the park is presented in Table 4 below, along with the storage capacity that must be considered in the park for hydrogen:

Production	Unit	Industrial park total
Electrolysis capacity	GW	28.3
Hydrogen production	kpta H2	437
Ammoniac production	kpta NH3	7,155
Derivates production	kpta H2 Equivalent	931
Hydrogen storage	ktH2	3.7

Table 4. Overview of the capacities of the H2 Mejillones Industrial Park.

Source: (Hinicio, 2023).

Based on these estimates of potential hydrogen and derivative production in the park, the land areas necessary to install the plants that would produce these volumes were sized. For this, estimated values of plant footprint requirements (or footprint) were used[7], according to the following information:

Module	Unit	Unitarian Footprint
Hydrogen Plant	m^2/MW	65
Ammonia conversion plant (includes ASU)	m^2/tpa NH_3	0.06
Conversion plant for other derivatives	m^2/tpa $H_{2\ equiv.}$	0.17
H_2 Storage	m^2/H_2	135

Table 5. Average footprint per unit of typical plant in the industrial park.

Source: (Hinicio, 2023).

Additionally, the following assumptions were considered:

[7] In the case of hydrogen plants, the footprint includes substations and transformers, the water treatment system, and the cooling system, whereas the ammonia plant includes the air capture system for nitrogen extraction.

- The footprint of the plants themselves corresponds to only 1/3 of the total gross area required. An additional 1/3 of the gross area is estimated as a buffer for other facilities, such as derivative storage, surface for internal roads and other necessary services in the park (e.g., logistics, operation, and maintenance, among others).
- The remaining 1/3 of space will be considered for other industries (including, for example, fertilizer and explosives plants, and other indirect derivatives), and other services that can be installed in the H2 Mejillones Industrial Park (workshops, maintenance services, warehouses, other logistics services, etc.), for the exploitation of synergies that will be generated on-site.

Based on this information, the final geographic sizing of the park is approximately 885 hectares. In this scenario, just as an example, 11 ammonia plants with a production capacity of 1 million tons/year could be located. The breakdown of estimated areas for the different components of the industrial park is presented in the following Table:

Module	Gross Power-to-X area (ha)	Buffer area (ha)	Total Industrial Park area (ha)
Hydrogen plants	184	368	Includes additional space for other industries and services in the industrial park
Ammonia conversion plant (includes ASU)	45	90	
Conversion plant for other derivatives	16	32	
H_2 Storage	50	100	
Total Area	295	590	885

Table 6. Estimated areas of the different units of the industrial park.

Source: (Hinicio, 2023).

In comparative terms, in relation to the projects indicated in section 1, the proposed production for the H2 Mejillones Industrial Park has similar values to the estimated projection for the Namibia Southern Corridor Development Initiative (SCDI). Meanwhile, the port and industrial complex of Pecém by 2030 will have a production of 49% of the H2 Mejillones park by 2050. However, it is expected that Pecém's capacity will grow along with global demand until 2050. The Park in Pecém doubles the dimensions of Mejillones due to the consideration of renewable generation plants in the former.

On the other hand, for the specific case of the Point Lisas Industrial Estate in Trinidad and Tobago, dedicated to the production of ammonia and fertilizers, it is an example that industrial parks with similar characteristics to those of the H2 Mejillones Park can host multiple industries and coexist successfully, even alongside urban development, presenting at the same time productive capacities and dimensions like those of the H2 Mejillones Industrial Park.

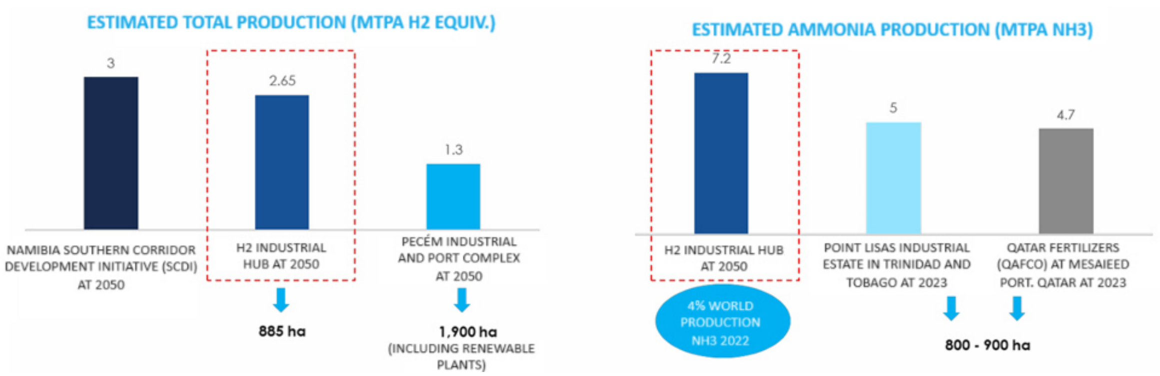


Figure 20. Comparative analysis of production and estimated area of the Mejillones Industrial Park.

Source: (Hinicio, 2023).

3.2 Location analysis of the industrial park

3.2.1 Territorial planning instruments in Mejillones

To identify suitable geographical areas in the municipality of Mejillones to establish the industrial park, an analysis of territorial planning instruments was conducted. The details of this analysis can be reviewed in (Hinicio 2023, H2 Mejillones Industrial Park).

The instruments regulating the urban and rural areas of the municipality are:

- Communal Regulatory Plan Ordinance for the Port and Bay of Mejillones.
- Ordinance No. 33 dated Nov 11, 2000, Regulatory Plan for the Port and Bay of Mejillones.
- Modification of Consolidated and Port Area.
- Small Industry Sectional Plan for Mejillones.
- Intercommunal Coastal Border Regulatory Plan for the Antofagasta Region (PRIBCA).
- South Coastal Sectional Plan.
- Mejillones Plateau Sectional Plan.

The Ordinary Circular 504 of the Urban Development Division (DDU) No. 470/2022 states that hydrogen generation falls under the "Energy Infrastructure" use type, while ammonia production is defined as "Productive Activities" use type according to the General Urban Planning and Construction Ordinance (OGUC) in its articles 2.1.29 and 2.1.28 respectively.

On the other hand, Productive Activities are classified on a case-by-case basis by the Regional Ministerial Secretariat (Seremi) of Health as harmless, bothersome, dangerous, or polluting, while Circular B32 from the Undersecretariat of Health instructs the Seremi of Health on technical criteria for this classification for substances regulated by D.S No. 43/2015, as hydrogen and ammonia are defined as "Hazardous Substances" according to NCh 328 of 2017. Therefore, in this study, it is considered that large-scale green hydrogen and ammonia production plants could be classified as "dangerous" according to current regulations. Despite this, areas were identified in the current Mejillones Communal Regulatory Plan where, from a conceptual point of view, the installation of a green ammonia industrial park would be appropriate, although currently, dangerous productive activities are not allowed.

Furthermore, Figure 21 shows the identification of two sectors defined by the current Mejillones Communal Regulatory Plan corresponding to "Port Area Zone" (ZAP) and "Port Area Zone 2" (ZP2), where harmless and bothersome Productive Activities are allowed, while dangerous, unhealthy, or polluting Productive Activities are prohibited. It was also identified that in both sectors, the use of land for Energy Infrastructure is not permitted.

Therefore, although the industrial park is operationally and logistically suitable due to its size and its location away from populated centers as well as close to port terminals, for the ZAP and ZP2 sectors to be used in the development of the industrial park, a modification of the current Communal Regulatory Plan is first required, which is estimated to take between 3 to 4 years.

It is worth noting that certainty about land use is relevant for the investment decision of projects and to realize the development of the H2 industry in Chile within the timelines contemplated in the National Strategy.

Figure 21. Optimal areas for the industrial park location.

Source: (Hinicio, 2023).

Additionally, extensive areas outside the urban boundary of Mejillones, as defined by the Communal Regulatory Plan, have been identified that could be considered for exploring alternatives for the installation of the industrial park. Figure 22 shows an alternative area identified as A2, where land use is regulated by the Coastal Border Intercommunal Regulatory Plan of the Antofagasta region (PRIBCA, Ministry of Housing and Urbanism, 2021), an instrument that is also in the process of being updated, with final approval expected in 2024.

In area A2, PRIBCA defines it as a ZEIC sector, a Zone of Conditional Industrial Extension, where exclusive industrial use is allowed for the placement of industries, sanitary infrastructure, transportation-related activities, and warehousing. Therefore, the installation of green hydrogen production plants is permitted, as they are considered energy infrastructure. However, the green ammonia plant, considered a Productive Activity, must be classified by the health authority as non-bothersome to be allowed, according to the PRIBCA ordinance.

Beyond the areas specified in the figures of the territorial analysis, it is possible to conclude that there are good location alternatives for the industrial park within the communal territory, whether urban or rural, as long as connections and adjustments to the existing infrastructure are made.

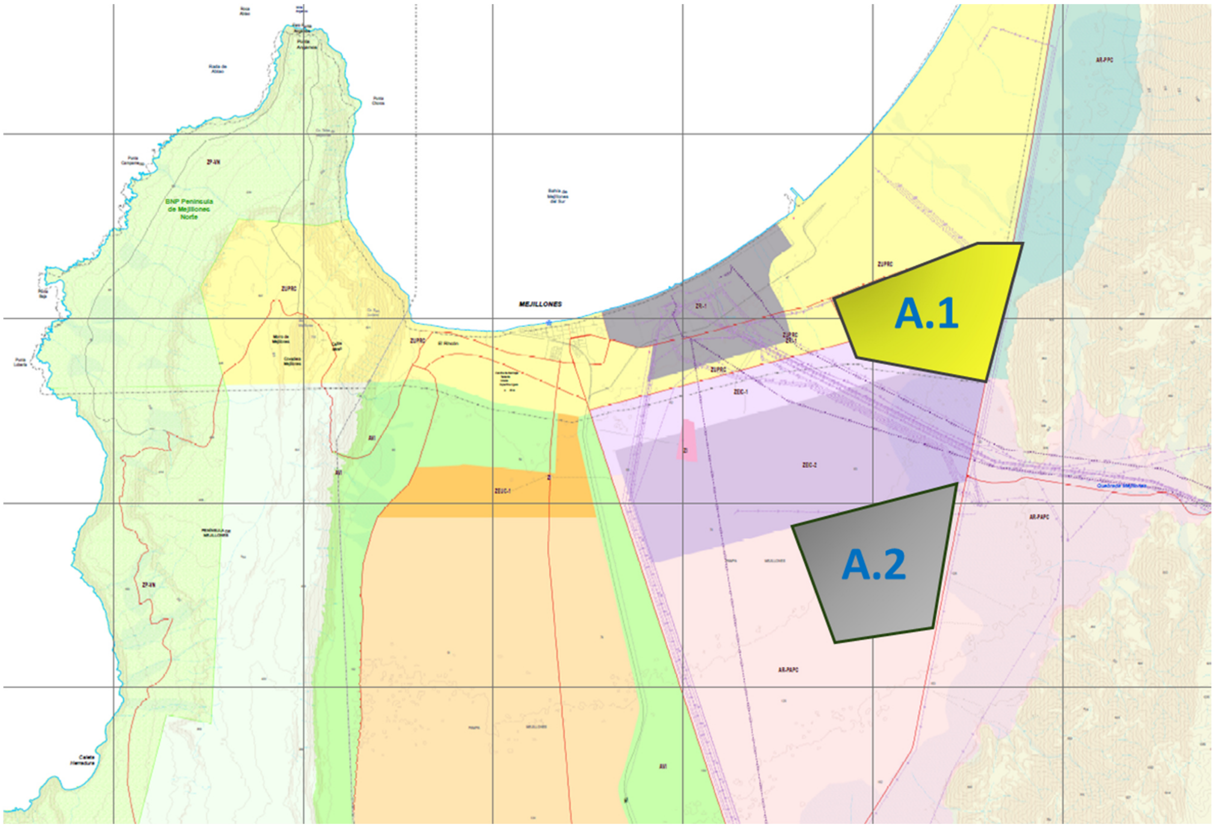


Figure 22. Optimal areas for the industrial park location.

Source: (Inodú, 2024).

In addition to the analysis of applicable territorial planning instruments, it is necessary to analyze the existing infrastructure from the perspective of availability and barriers to land use. Considering this perspective, a review of the urban area of Mejillones was conducted, where the presence of areas with network layouts (power lines, gas pipelines, aqueducts, railways) was confirmed. This can be seen as both a benefit and a disadvantage. While their proximity facilitates the project's connection to these networks, they also limit land use by fragmenting it. Figure 23 shows the location of the main infrastructure network layouts.

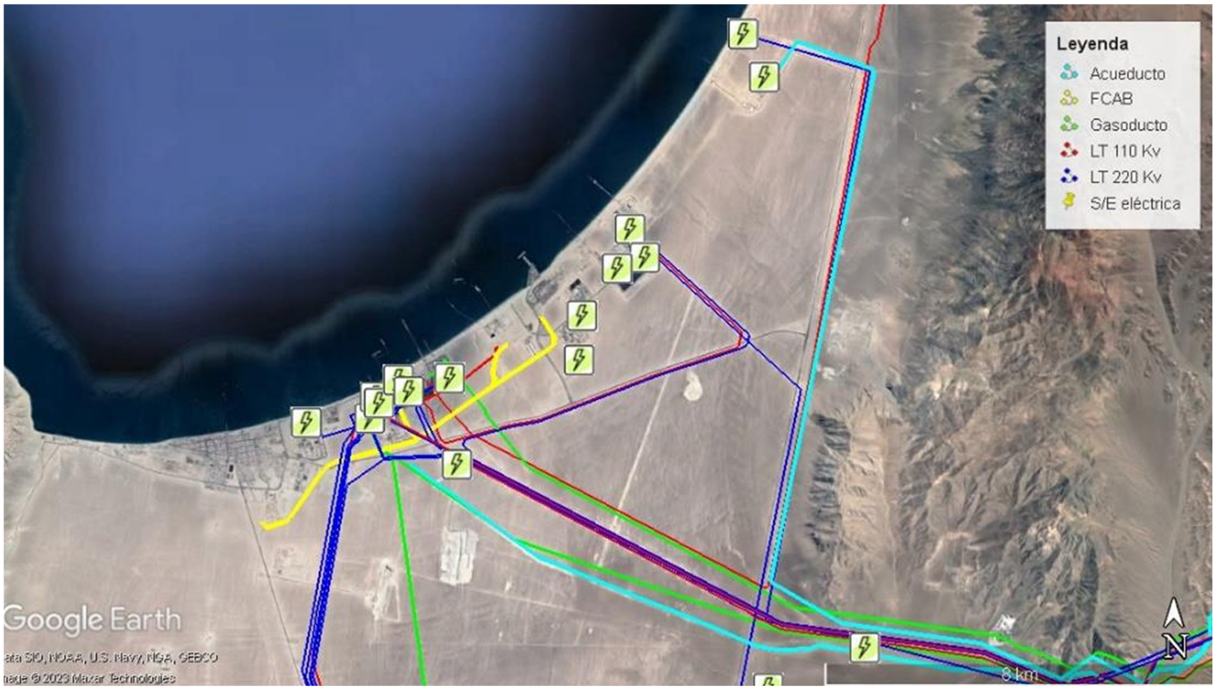


Figure 23. Network layouts in the Mejillones area.

Source: (Hinicio, 2024).

In the territorial analysis, it is also necessary to consider the existence and nature of mining concessions in the alternative areas. If established concessions already exist and there are feasible mining projects in each region, these areas would not be available for other industrial projects. The regulatory framework applicable to mining rights has undergone modifications in recent years to provide certainty for the development of projects. In this context, it is considered that reserving a strategic area with the participation and support of the State for the implementation of an industrial park could provide legal certainty for the installation of projects in that area.

3.2.2 Environmental and community considerations

In addition to territorial aspects for project conceptualization, it is necessary to analyze environmental and social aspects to propose viable location alternatives for an industrial park.

It is important to note that when studying environmental aspects of a territory, multiple factors and variables present in the project's influence area must be addressed, including identifying the presence of native fauna in the study area. An example of this is identifying some species in conservation categories in the area analyzed for the industrial park. According to the Environmental Impact Assessment (EIA) of the Volta Project by the MAE company (Jaime Illanes & Associates, 2024), there are two endangered species in the area (the black storm petrel and the least tern). Due to their importance, the *Gaviotín Chico Foundation* was established in 2008, responsible for monitoring and conserving this species.

The recent information provided by this EIA indicates that although there are historical nest records provided by ROC (Chilean Network of Bird and Wildlife Observers), no nesting areas for these species were identified in the field survey in the zones being evaluated for the industrial park location, as illustrated in the following figure:

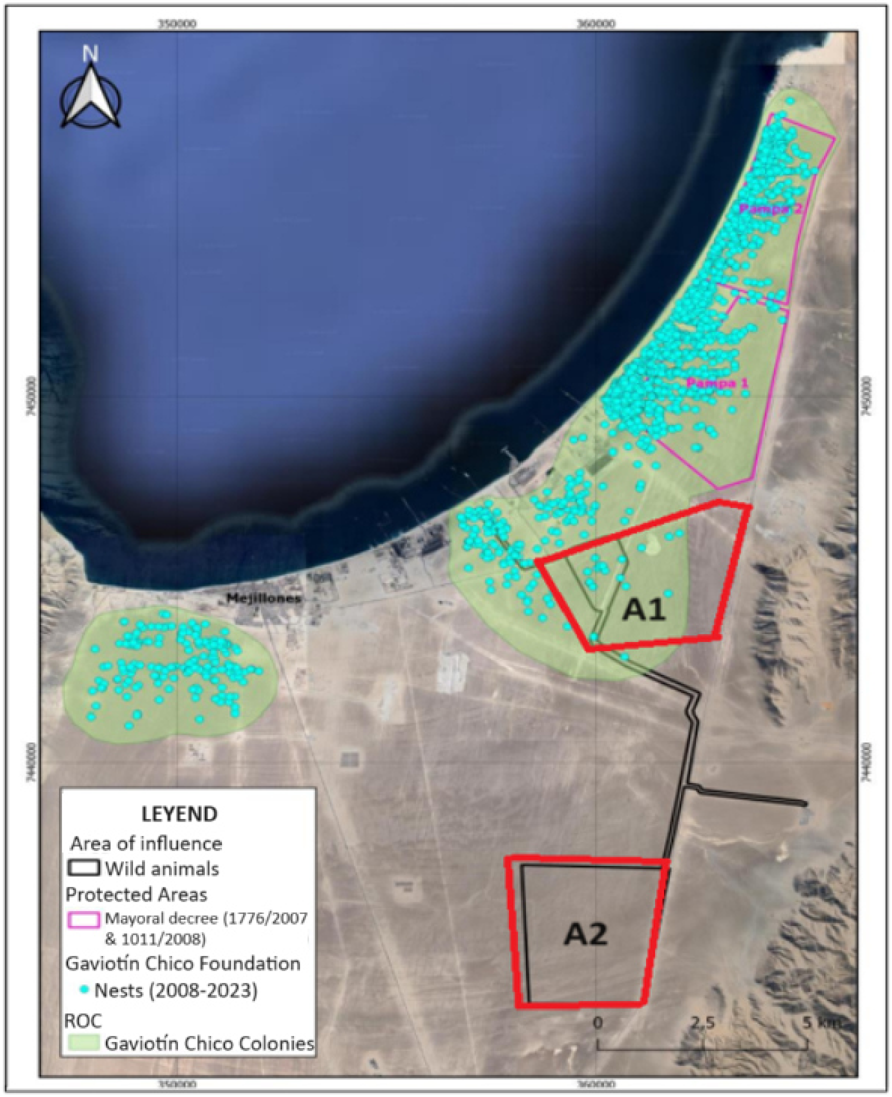


Figure 24. Gaviotín Chico (Sterna Lorata) nesting area.

Source: (Jaime Illanes & Asociados, 2024).

This information is confirmed, by the fact that the locations considered for the industrial park are outside the areas protected by municipal decrees (N°1776/2007 and N°1011/2008) for the protection of this species in the communal territory. In this context, the sectors preliminarily considered for the industrial park in this work are not located in nesting areas or protected areas according to the available information.

However, all projects located in the industrial park must also undergo the Environmental Impact Assessment System (SEIA) through a declaration or environmental impact study as appropriate, considering all components and defining the corresponding influence areas.

Regarding social aspects, it will be necessary to conduct, in a subsequent stage, a detailed and thorough survey of the characteristics of the involved communities and the positive and negative economic and social impacts of developing an industrial park in the communal territory. At this stage, it can be observed that the commune currently has a markedly industrial and port character, with the presence of significant companies linked to the energy sector (thermoelectric plants), logistics (port infrastructure), and production of mining supplies (explosives, sulfuric acid, etc.). This characteristic of the commune presents both advantages and challenges in relation to the acceptance of future companies by the communities. On one hand, these are familiar activities with which the citizens of Mejillones have learned to coexist for more than 40 years. On the other hand, past experiences with industries have not always been positive, due to negative environmental externalities such as atmospheric pollution or seabed contamination.

In this context, it is appropriate to propose the development of an industrial park that addresses one of the problems caused by inorganic industrial growth in the past: territorial fragmentation and inefficient use of the coastal edge. A long-term planned industrial park development allows for overcoming fragmentation and making more efficient use of the territory and coastal edge. Additionally, it seems convenient to locate the park away from populated centers and the coastal edge, to minimize potential risks to the current population associated with the transport and handling of hazardous substances and limitations to long-term urban growth.

Regarding social and community aspects, it is also appropriate to consider the advantage that the industrial park proposal can represent. It is suggested to consider conducting a strategic environmental study with early public participation. This process of dialogue with the communities can be developed with an overarching vision of the industrial park, with its potential benefits for the local economy and the environment, and with a few public and private promoters as its proponents. This is a relevant activity that should be addressed in a subsequent stage of the industrial park implementation design.

The mentioned environmental and social considerations have been considered for the preliminary proposal of alternative locations, but they are not within the scope of this work. They should be thoroughly addressed through specific environmental studies according to the applicable regulations during the subsequent stages of the industrial park design and implementation, and later also by each of the projects located within it.

3.3 Master plan of the H2 Mejillones Industrial Park

Based on the sizing and territorial analysis presented in the previous sections, a master plan proposal was developed for the long-term development of the industrial park, with a horizon until 2050. The proposal presented in Figure 25 is based on an illustrative location only, useful for showing some aspects for further design. The exact locations will need to be analyzed in greater depth in conjunction with the competent authorities to arrive at a definitive definition as appropriate.

In fact, at the location shown in the figure, there is a project that recently submitted its Environmental Impact Assessment, the Volta Project by the MAE company (Jaime Illanes & Associates, 2024), whose industrial plants will occupy a total area of 38 hectares according to the mentioned EIA. This certainly does not mean that the entire area indicated in the master plan (900 hectares) is disqualified for park development; rather, it indicates that it is indeed a favorable location to install this type of project, which merits further study in coordination with the MAE company.

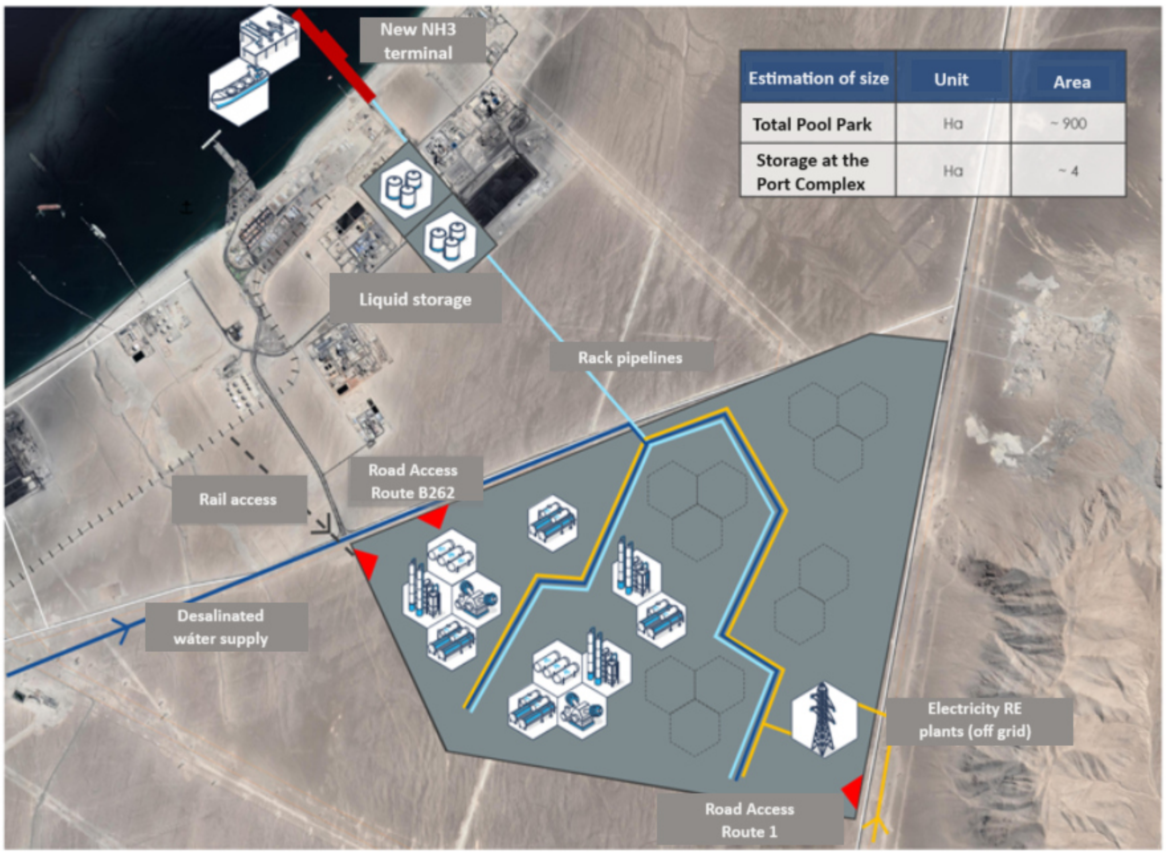


Figure 25. Master plan of the H2 Mejillones Industrial Park.

Source: (Hinicio ,2023).

Figure 25 shows, as reference, the possible road and railway accesses to the industrial park, its connection to the port through a pipeline corridor, the aqueduct for the common supply of desalinated water to the plants, the infrastructure for power transformation and transmission, among others. It is contemplated to install large storage tanks for products in the port area, which would be about 5 km away from the park, with a requirement for areas of at least 4 hectares.

It is worth noting again that the main purpose of this master plan is to provide a foundation for strategic land reservations that enable long-term planned development, and clear location signals for private industrial projects. On the other hand, the master plan aims to show public and private actors a viable way to develop an industrial hub that contributes to the competitiveness and sustainability of the emerging green hydrogen and derivatives industry.

The advantages for a private project to be located within the proposed industrial park in Mejillones are numerous. At this stage, some qualitative advantages that each individual project can evaluate as the park implementation progresses and relevant parameters for economic evaluation are defined can be mentioned, such as:

- Quicker access to land in a planned area if the state reserves an area of public lands for this purpose and defines appropriate instruments for accessing them under transparent and non-discriminatory conditions.
- Lower environmental and community risks, as environmental baseline studies progress in the park area and associated infrastructure, and benefits are early socialized for acceptance by communities.

- Shorter timelines for obtaining permits, as progress is made on environmental baseline studies and community issues, the scope and timing of studies, and permit processing are reduced.
- Reduced development and financing risks. Projects must manage various risks during the development stage, which often result in demanding financing conditions. As these risks decrease due to being located within an industrial park for the mentioned reasons, financing conditions can also be improved, which can have a significant impact on the competitiveness of these capital-intensive projects.
- Access to service companies and equipment suppliers that are established in the industrial park, with the resulting advantages of supply costs.

There are also other advantages for which some quantitative estimates can be provided that may guide location decisions, such as:

- Open access to shared port infrastructure for product export and import of industrial equipment, including pipelines and storage tanks. In the case that a project does not have shared infrastructure and must build its own port and storage facilities to export its products, the project's CAPEX would increase by at least 200 million dollars. And by not accessing economies of scale for these services, OPEX would also increase significantly (Hinicio, 2023).
- Availability of desalinated/demineralized water based on shared infrastructure (desalination plant and aqueducts). In the case that a project must build its own desalination plant (e.g., with a capacity of 50 l/s), the project's CAPEX would increase by approximately 8 million dollars, and associated OPEX increases by at least 25% (Self-generated, 2023).
- Dedicated power transmission lines and shared substations. If 4 projects (with a capacity of 1,000 MW and 80 km in length) share investments for a 500 kVA transmission line, the investment for each would be approximately 65 million USD, 40% less than if each project builds its own 220 kVA line with an approximate cost of 108 million USD. In addition to the additional development costs and associated timelines to enable two strips of land with their respective permits for each line (Inodú, 2023).
- Rail and road access. The costs of road and railway accesses required for a project depend on its location and distance to existing infrastructure. But if these accesses are resolved in an industrial park, investments in this high-cost infrastructure are significantly reduced, reducing the project's CAPEX (Izquierdo, 2023).

4 Conceptual design of a green ammonia plant at the Mejillones Industrial Park

The purpose of this chapter is to present the conceptual design of a green ammonia production plant, which would be located within the proposed industrial park in Mejillones. With this, the aim is to show some advantages of being part of the planned industrial park, regarding the shared use of enabling infrastructure and its potential to improve competitiveness and sustainability.

The design includes a technical-economic optimization of the system in two stages, an initial phase that will be fully operational in 2028 and a second phase that will start operation in 2035, in addition to the system's configuration. The purpose is to understand the timing and optimal scale of the model plant in the Mejillones Industrial Park, to produce ammonia at the lowest levelized cost possible.

The approach adopted to achieve this objective is, on the one hand, to maximize the advantages and potential synergies of locating the model plant within the industrial park. On the other hand, it seeks to optimize the entire value chain associated with green hydrogen and ammonia production, maximizing the region's renewable energy resources, and using formal tools for systematic optimization of the project's design and operation.

The design optimization process included several studies addressing different components of the value chain. A first study (Suazo, 2023) addressed the analysis of renewable resources in the region and preliminary optimization of the power supply system for production plants, as well as a survey of regional infrastructure and a preliminary analysis of locations for components of the value chain. Another study (Izquierdo, 2023) addressed the logistics of transport and storage of the main products, hydrogen, and ammonia, to incorporate their relative costs into the analysis of locations for different components of the production system.

A third study (Yáñez, 2023), considering the results of the previous ones, used a systemic approach to integrate the different components of the value chain and perform a global optimization, based on the conceptual design of the different plants. This last study allowed estimating investment and operating costs of the system and obtaining preliminary results for the levelized costs of green hydrogen and ammonia production.

In addition, another consultancy commissioned to Hinicio provided a formal tool developed by that company to size and optimize the entire production system at a pre-feasibility level. This study integrated the different aspects and components analyzed previously and produced the desired results in terms of plant design, CAPEX and OPEX estimates, and levelized costs of the system.

The following sections describe the approach to selecting the technologies of the main plants, the optimization process of the production system and plant capacities, and finally, the conceptual design of the model plant in its two development stages, including the sizing of its equipment and plants, investment and operating costs, and main results in terms of levelized production costs.

4.1 Technology selection and economies of scale

The value chain of an ammonia synthesis project from renewable energy electrolysis comprises various processes and technologies, including renewable electricity generation, high-voltage electrical transmission, hydrogen production, compression and storage, nitrogen production, ammonia synthesis, and its transportation and storage.

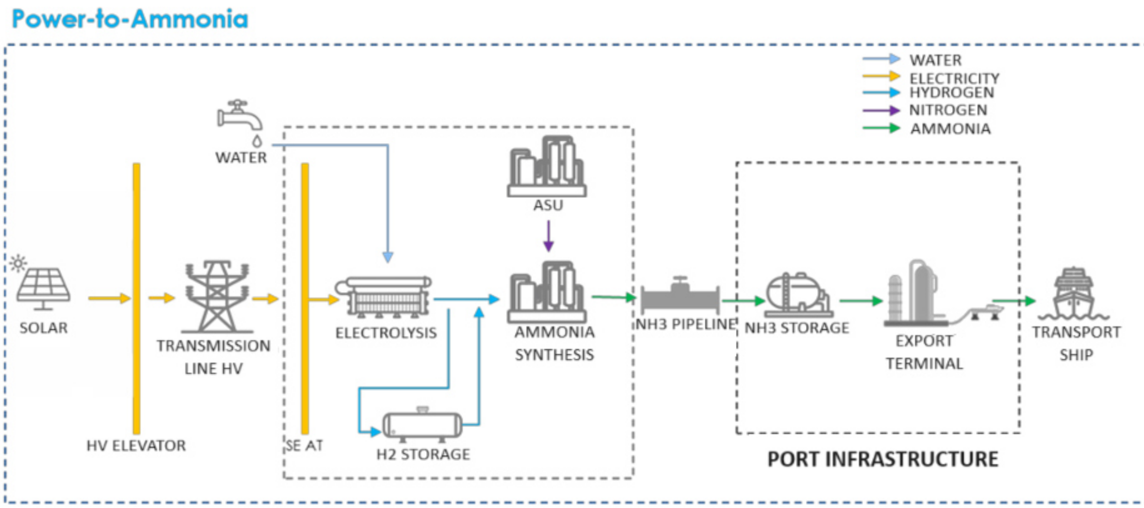


Figure 26. Power-to-ammonia project chain of value.

Source: (Hinicio, 2023).

4.1.1 Electrolysis process

For the selection of green hydrogen production technology through water electrolysis, this project considered alkaline electrolysis (AWE), proton exchange membrane electrolysis (PEM), and high-temperature electrolysis (SOEC).

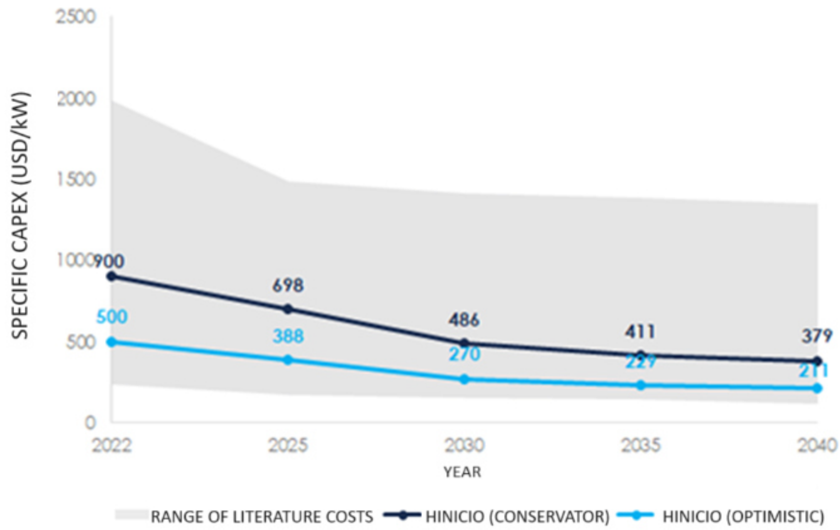
Alkaline electrolysis is based on an electrochemical process that uses an alkaline solution as an electrolyte, usually potassium hydroxide (KOH). Among the advantages of AWE electrolyzes, it can be noted that it is currently the most mature technology, has been used for years on an industrial scale with production levels in the MW range, has the lowest specific CAPEX, and the longest lifespan compared to other technologies.

Proton exchange membrane electrolysis (PEM) is a mature technology that uses a solid proton-conducting electrolyte. In this process, the protons produced by electrolysis are transported through the electrolyte from the anode to the cathode. With PEM technology, the high operating pressure reduces the need for downstream compression, it has a wide operating range and a compact design that allows it to work in projects with space constraints. However, its lifespan is shorter compared to AWE electrolyzers, its capacity in the MW scale is recent, it has a high material cost for stack construction, and therefore a higher specific CAPEX value.

Finally, SOEC electrolysis is a technology that is still under development, requiring a heat source and lower electricity consumption. In this process, O2- anions produced are transported through a solid electrolyte from the cathode to the anode. SOEC technology has a high level of theoretical efficiency, with a catalyst that does not require noble metals, reducing its cost. However, the stack of this technology requires long start-up and shutdown times, which do not allow flexibility in production intermittency. Additionally, this technology has a limited cell size, requires an additional heat source, has high investment costs, and there are currently no industrial-scale plants.

To select the most efficient technology for the project, a CAPEX analysis was conducted. This analysis was done according to current technology and in the year 2040. Costs associated with each technology were considered, including the stack and plant balance for each equipment.

Figures 27, 28 and 29 show the obtained CAPEX:



Source: (Hinicio 2023).

Figure 27. Estimation of CAPEX for AWE electrolysis.

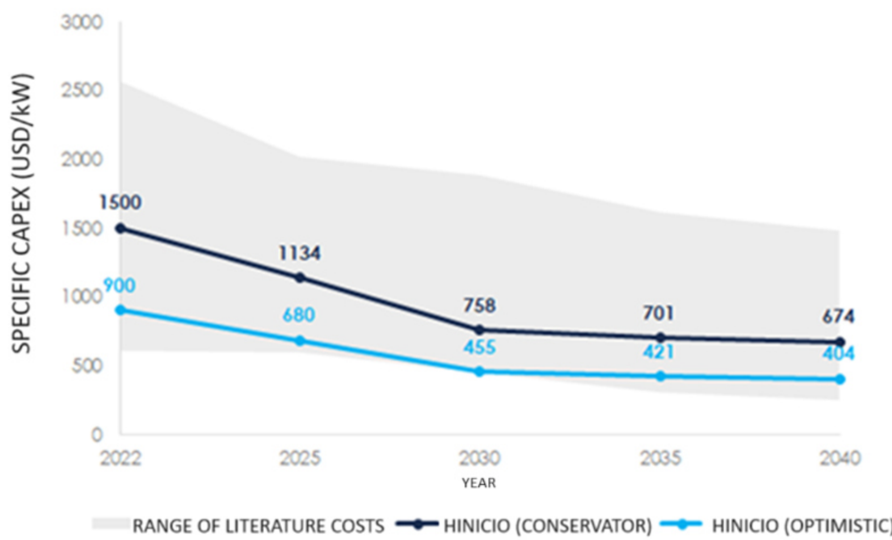


Figure 28. Estimation of CAPEX for PEM electrolysis.

Source: (Hinicio 2023).

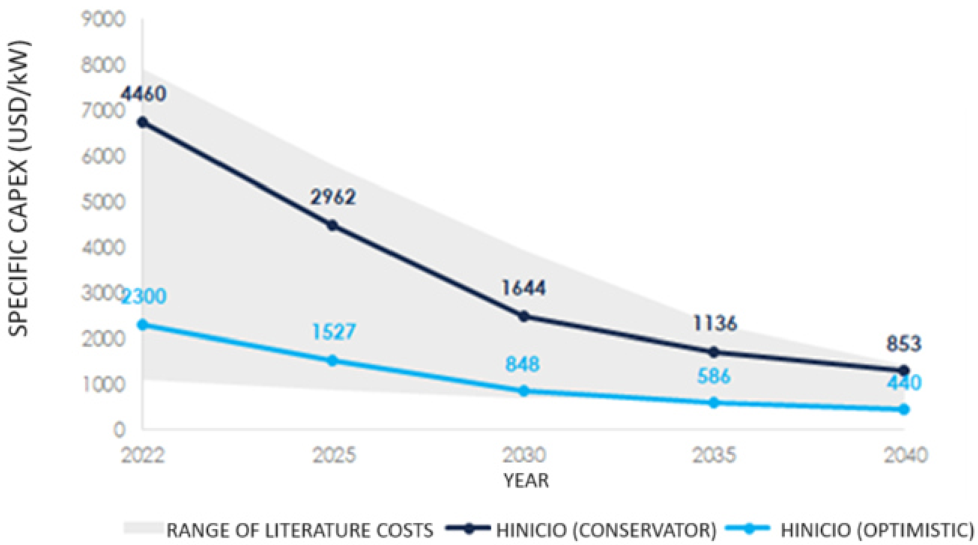


Figure 29. Estimation of CAPEX for SOEC electrolysis.

Source: (Hinicio 2023).

Based on these CAPEX projections, a high-level analysis of the levelized cost of hydrogen (LCOH) was also conducted to compare electrolysis technologies. This analysis considered a stack reinvestment every 12 years of operation, a stack degradation of 1% per year, and an electrolysis plant operating at base load without interruptions (24/7). Additionally, an electricity cost of 70 USD/MWh and a water cost of 2 USD/m^3 were assumed.

AWE electrolysis has the lowest LCOH, with current values of approximately 4.5 USD/kg of H2 and about 4.0 USD/kg for the year 2040, and it has greater confidence in the expected reduction of CAPEX. On the other hand, PEM technology shows current LCOH values of around 5.5 USD/kg and 4.5 USD/kg of H2 for the year 2040. SOEC technology presents the highest current LCOH values, approximately 7.5 USD/kg, but a significant reduction is projected until the year 2040, down to 4.0 USD/kg H2, although with a lower degree of confidence in this reduction. It is important to mention that this LCOH analysis is referential and high-level, and its results should be interpreted with caution, as electricity and water costs were assumed, but the value of these costs impacts the selection of technology differently. For example, low electricity costs (~30 USD/MWh) decrease the advantage of SOEC technology with its lower electrical consumption compared to AWE and PEM technologies.

As a conclusion from the analyses conducted, it is suggested to select AWE technology for the model plant, as it achieves lower CAPEX and LCOH, both currently and in projections for the year 2040. Additionally, this technology is currently the only one that can demonstrate its capability to reach industrial scales of hundreds of MW, which is the scale required by the model plant. Finally, it is projected that this technology will cover about 60% of the market by 2030, and soon, it will have production equipment of around 100 MW, which reinforces its comparative advantages over other types of electrolyzers.8

[8] In terms of the space occupied by the plant, an alkaline electrolysis plant typically requires almost twice the area of a PEM plant. Therefore, PEM electrolysis technology will be the logical solution for projects with significant space limitations. However, in the case of the industrial park, space limitation does not seem to be a critical parameter for deciding the optimal electrolysis technology.

Nevertheless, it is recommended to monitor alternative technologies, PEM and SOEC, as the conclusion indicated could change in the face of disruptive changes and operating conditions or relative prices of the main parameters impacting the LCOH of these technologies.

4.1.2 Ammonia synthesis

The main technology for ammonia production since the early 20th century is the Haber-Bosch process. In general terms, this process involves the catalytic reaction of a gaseous mixture of hydrogen and nitrogen, previously brought to high temperatures and pressures, to obtain ammonia. The conversion rate is usually between 15% and 20% for each individual cycle. Therefore, a large internal recycling is required to achieve a high overall conversion (up to 98%).

Currently, there are Haber-Bosch plant designs with production capacities between 4,000 and 6,000 tpd, and typical capacities of ammonia plants fed with gray hydrogen are between 2,000 and 3,500 tpd in continuous process (IRENA, Global Trade Hydrogen, 2022).

The specific CAPEX of a Haber-Bosch plant is observed in Figure 30. When the capacity is greater than 500 tpd of NH3, the specific CAPEX decreases from 218,000 USD/tpd NH3, and when the capacity is higher than 2,000 tpd NH3, the specific CAPEX stabilizes at around 108,000 USD/tpd NH3 approximately. However, already from 1,000 tpd, it enters a zone with few variations in costs. Plants over 1,000 tpd already have thermal integration to recover heat and generate electricity through recuperative turbines (higher efficiency). In scenarios of growth, increasing the number of trains in this capacity can be considered to increase production according to a phased development.

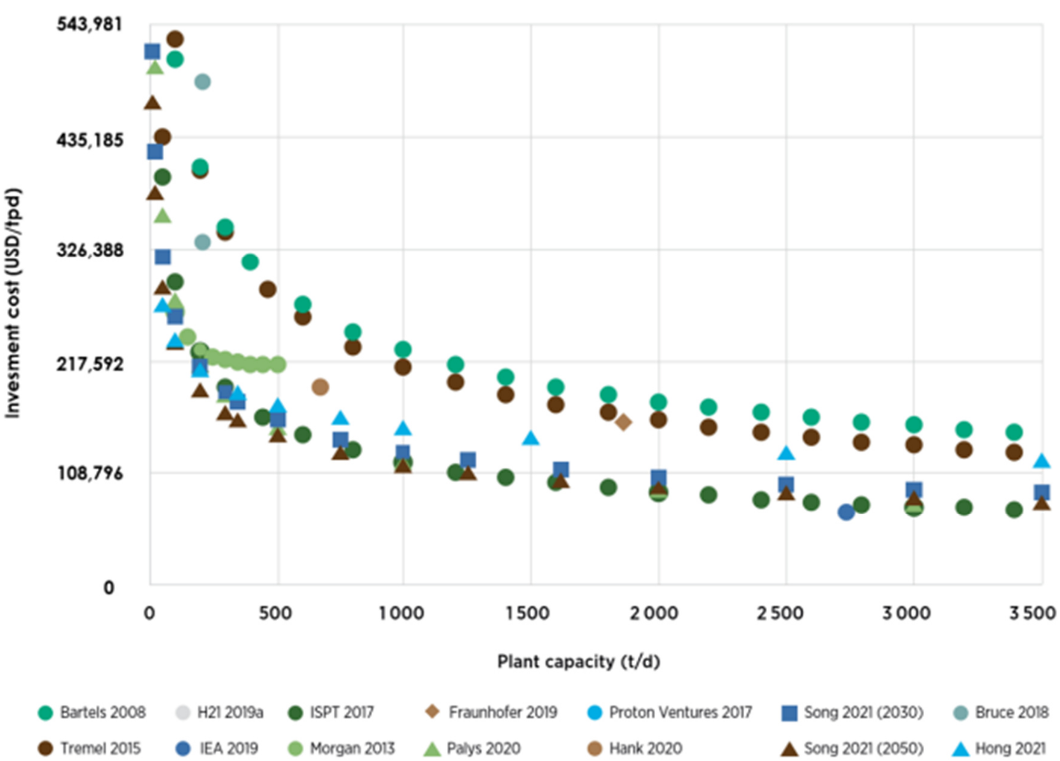


Figure 30. Specific CAPEX for Haber-Bosch plant.

Source: (Hinicio, 2023).

4.1.3 Air separation

For ammonia production, not only hydrogen is needed but also nitrogen. Currently, there are three types of technologies that allow isolating the nitrogen contained in the air: cryogenic distillation, pressure swing adsorption (PSA), and membrane separation, where cryogenic distillation represents more than 90% of the world's nitrogen production and is the most cost-effective option for large-scale nitrogen production plants, with a high technological maturity.

Considering the nitrogen needs for a daily production plant of 1,000 NH3, 35,000 kg N2/h or 28,000 m3 (STP)/h are required, approximately. As the industrial park is expected to be of those sizes, cryogenic distillation technology is the recommended technology for nitrogen production.

For cryogenic distillation, costs vary according to production capacity as shown in the following figure:

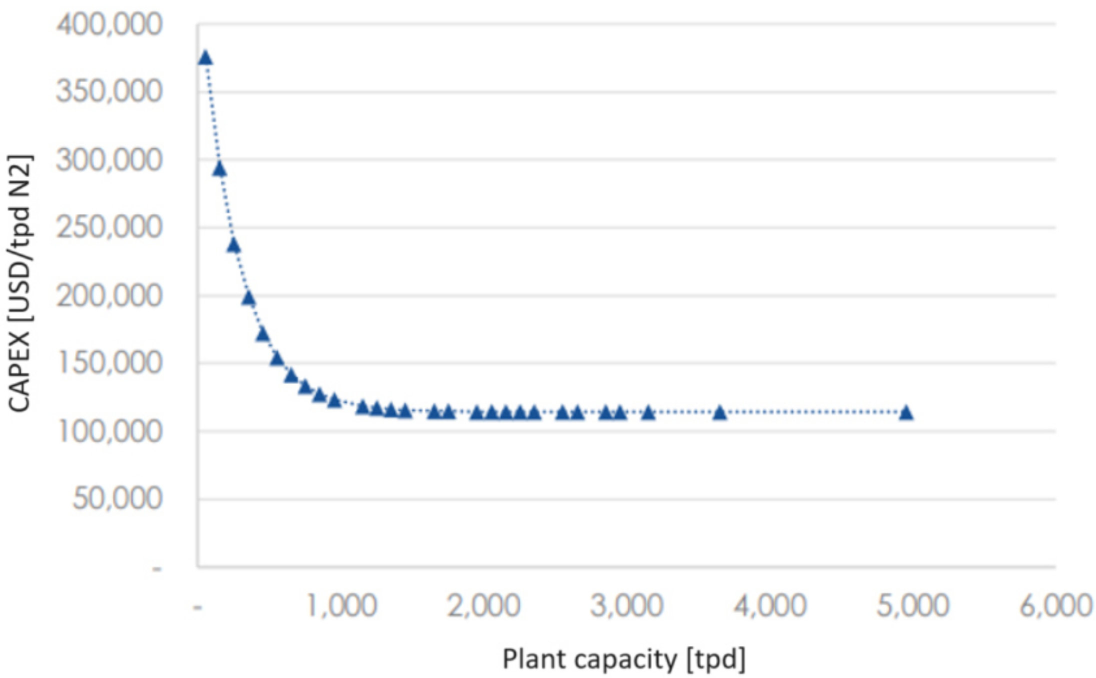


Figure 31. Cost of cryogenic distillation relative to nitrogen production capacity.

Source: (Hinicio, 2023).

Considering this information, it is possible to observe that when the plant capacity is 400 tpd NH3 approximately, the cost associated with renewable hydrogen production stabilizes. Around 700 tpd NH3 capacity, the cost associated with air separation unit stabilizes. The trend shows a similar conclusion to what was observed with the ammonia plant alone, that already from 1,000 tpd NH3, plants enter a zone with low-cost variations.

4.1.4 Economies of scale of an integrated system

According to the information presented, the model plant considers an integrated system for producing ammonia composed of alkaline technology for renewable hydrogen generation, cryogenic distillation for nitrogen production, and a Haber-Bosch plant for ammonia production.

Figure 32 shows the specific CAPEX of this integrated system as a function of the daily production volume of ammonia. The curve shows that from a production of 1,000 tpd, the specific CAPEX stabilizes due to additive economies of scale of the three processes. Beyond this value, variations in production capacity significantly reduce their impact on the specific costs of the technologies.

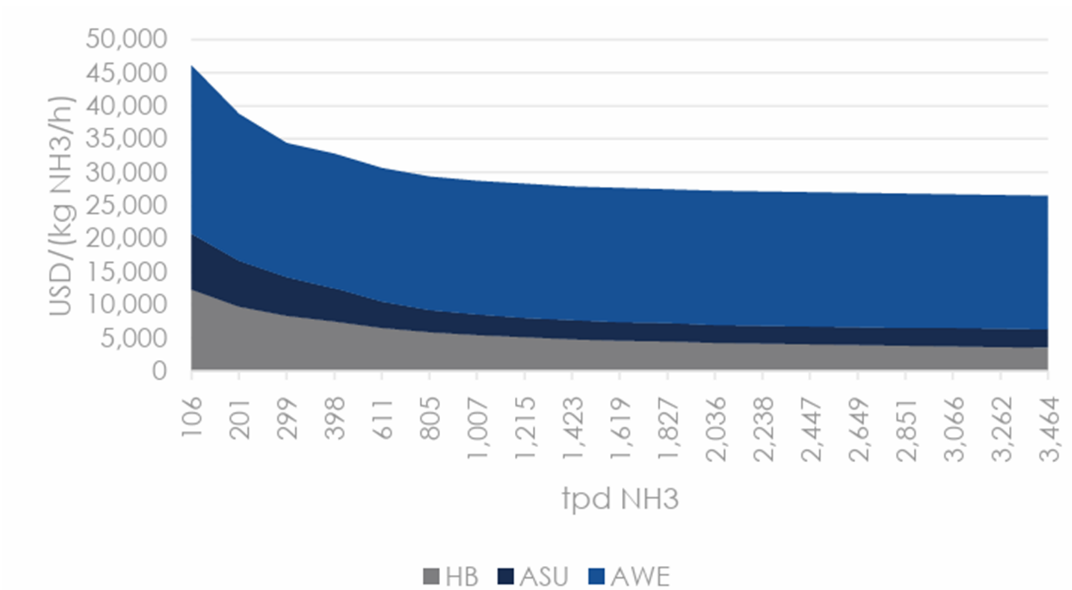


Figure 32. Economics of scale of integrated ammonia production system.

Source: (Hinicio, 2023).

4.2 Model plant configuration

The designed model plant will be located within the proposed industrial park, near the Mejillones Port Complex (5 to 15 km away) and will have an electrical supply through a photovoltaic plant located about 80 kilometers to the east, supplemented by PPA supply contracts. To determine the optimal configuration of the Power-to-Ammonia project, a technical-economic optimization is carried out, aiming to minimize the total cost of the system for the entire project's lifespan.

4.2.1 Production capacity selection and scaling

For the selection of the optimal production capacity, a preliminary analysis was developed, estimating the LCOA of three different ammonia production capacities (500 tpd, 1,000 tpd, and 2,000 tpd) for two alternative configurations:

- Base Case: The ammonia production plant operates constantly during the day at nominal production capacity.
- Alternative Case: The ammonia production plant operates flexibly, considering the recommended minimum technical operation for this technology (30% of nominal capacity).

This analysis was conducted to understand the impact that *Power-to-Ammonia* project scale and plant operational flexibility have on LCOA and CAPEX of such projects.

For the base case, the PV plant capacity, electrolysis system, and hydrogen compression and storage are oversized to operate the Haber-Bosch plant at 100% of its production capacity. In the alternative case, the ammonia plant is allowed to operate up to 30% of its nominal capacity, reducing electricity and hydrogen requirements.

The levelized cost of ammonia for the alternative cases is about 100 USD/t NH3 lower than that of the base cases of the same capacity. The total investment cost of the alternative cases is up to 26% lower than that of the base cases. The lower levelized cost of ammonia is obtained for the alternative case of the largest evaluated plant size (2,000 tpd), with an LCOA of 767 USD/t NH3. However, this cost is only 1.9% lower than the LCOA of the 1,000 tpd plant, but with an investment cost 87.4% higher than this case.

Considering the initial results, it is noted that economies of scale for ammonia plants with capacities above 1,000 tpd do not have a significant impact on the total system LCOA. Therefore, for the model plant, an initial capacity of 1,000 tpd is proposed for the first phase (operating from 2028), with the possibility of scaling up to a capacity of 2,000 tpd in a second phase (operating from 2035), using the evaluated alternative case configuration.

The second phase would consist of doubling the initial capacity by adding an additional production train to the system, as shown in the following figure:

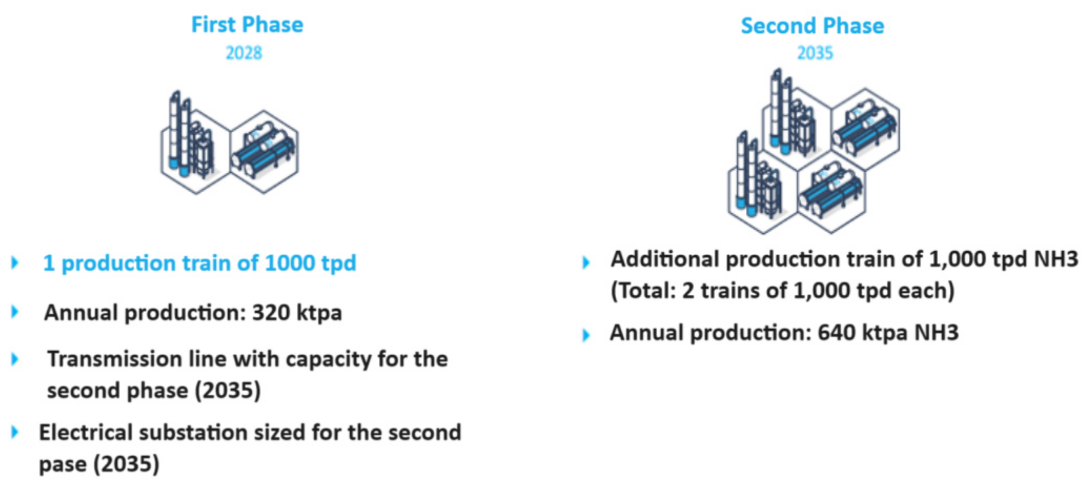


Figure 33. Green ammonia production units of the project in both phases.

Source: (Hinicio, 2023).

4.2.2 Optimal configuration

- **First phase (2028)**

The optimal design of the first phase of the project considers a 1.1 GW photovoltaic solar plant as the main source, supplemented by a 12 MW BESS[9] that stores electricity during solar hours and a renewable PPA *take or pay* of 22.1

[9] It will facilitate a reduction in curtailment of the PV plant during daylight hours, while optimizing energy utilization during periods of diminished solar resource availability, such as at night.

MW during the night to maintain ammonia plant operation. An 80 km transmission line of 1.68 GW is considered, oversized to transmit the electricity generated in the PV plant, both for the first and second phases of the project.

Regarding the hydrogen production plant, the design considers an 800 MW alkaline electrolyzer that produces hydrogen at 30 bar, a hydrogen storage system in type I tanks at 200 bars of pressure with a capacity of 100 tons of green hydrogen per hour, and a hydrogen reciprocating compressor with a capacity of 8 tons of hydrogen per hour.

For nitrogen production, a 34-ton per hour cryogenic air separation unit (ASU) is considered, while for ammonia production, a 42 tph (1,000 tpd) Haber-Bosch plant using the hydrogen and nitrogen produced in the previously described processes. Considering the available electrical supply, the optimal annual production of this system is 320 kt NH3/year.

It is worth noting that ammonia production essentially depends on hydrogen availability. During the day, ammonia production remains constant at its maximum capacity because the amount of green hydrogen produced is higher than required, so part of it is compressed for storage. During the night, when there is no solar resource availability and renewable energy is more expensive, the hydrogen storage tank is discharged to maintain ammonia production plant operation at the technical minimum (30%).

The produced ammonia is sent via an 8 km long 20-inch pipeline to the Mejillones Port Complex, where it is stored for later export to the Rotterdam port. It is assumed that both the pipeline transport, ammonia storage, and port services are provided by a third party. For the export of produced ammonia, vessels with a total storage capacity of 50,000 t (73,260 m3) of ammonia are considered.

Figure 34 presents the annual consumptions and capacities of each system considered in the conceptual design of the model plant in its first phase.

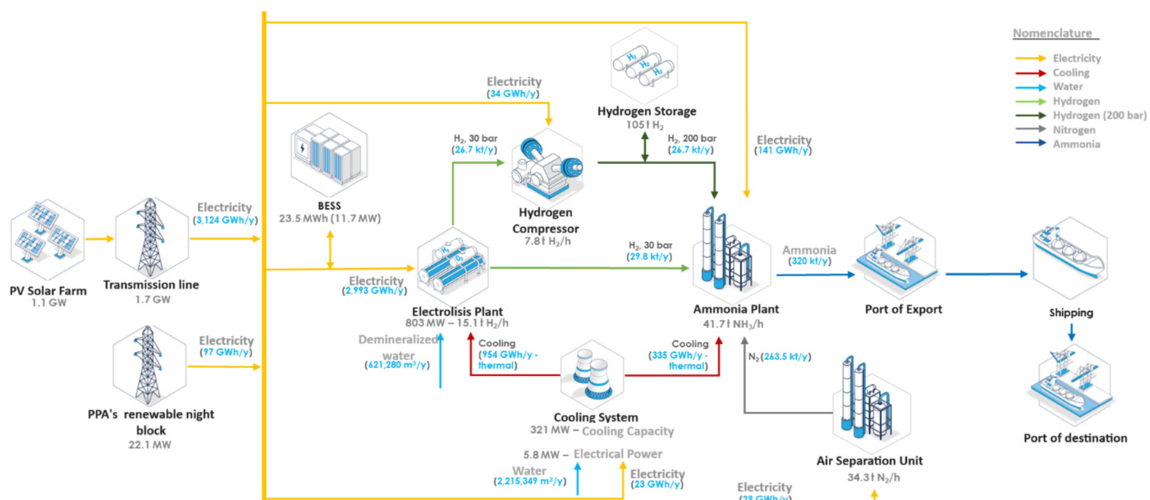


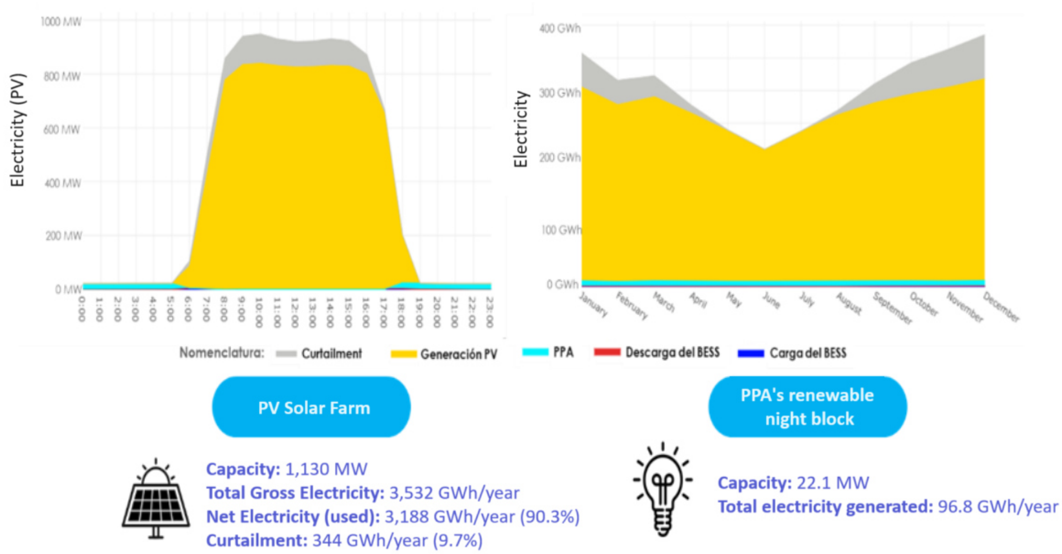
Figure 34. General mass and energy balance diagram for Phase One of the Project.

Source: (Hinicio, 2023).

Due to the annual variability of solar resources, the PV plant was sized to meet the electrical requirements of the system in June, a month with lower solar resource availability. Therefore, between September and March, months with higher solar resource availability, there is a higher curtailment of the PV plant, an energy volume that is not considered useful for the analysis conducted.

Electricity production during June is lower than in January, generally with production below 800 MW during solar hours and not reaching the maximum solar production capacity during the day. In contrast, in January, except for exceptional days of low production, the PV plant produces the maximum possible (860 MW) to harness the solar resource present in this month.

Figure 35 shows the results of the optimized electrical supply system sizing.



Source: (Hinicio, 2023).

Figure 35. Optimized electrical supply system.

The PV plant produces daily between 6:00 and 18:00, on average. During hours with no solar generation, the renewable PPA operates at night, supplying energy to the chemical plants to maintain the ammonia production plant's technical minimum operation. Regarding electricity consumption, 3,220 GWh/year is consumed by the production plants, 89% of the total system's generation. The electrolysis plant is the production plant with the highest electricity consumption, requiring 2,993 GWh/year, corresponding to 93% of the total energy consumption of the system.

On the other hand, the Haber-Bosch plant, for ammonia production, requires 140.8 GWh/year of electricity, corresponding to 4.3% of the total energy consumption. Hydrogen compression, cooling system, and ASU together consume 85.8 GWh/year, 2.7% of the annual system consumption.

Finally, for consideration, hydrogen compression, cooling system, and ASU together consume 85.8 GWh/year, 2.7% of the annual system consumption.

The production and consumption of electricity are presented in the following figure:

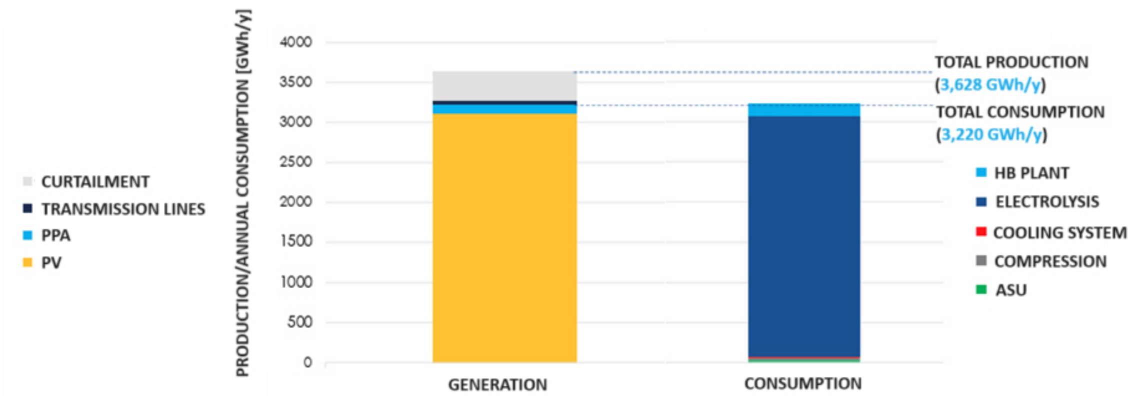


Figure 36. Production and annual electricity consumption.

Fuente: (Hinicio, 2023).

Next, the production curves of the main products throughout the year are plotted, adjusting to the solar resource availability:

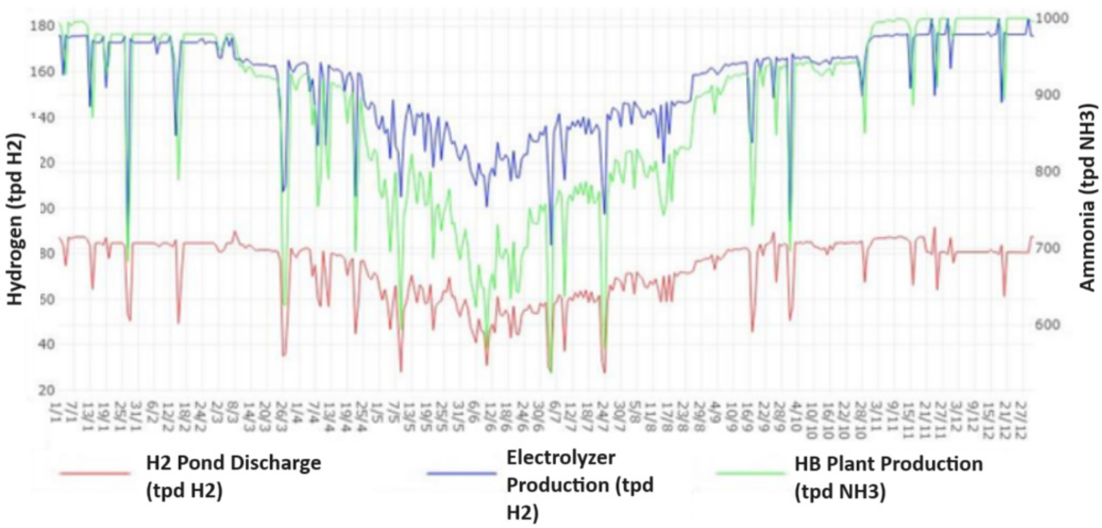


Figure 37. Green hydrogen production curves throughout the year.

Source: (Hinicio, 2023).

- ### Second phase (2035)

The second phase of the project for the model plant involves adding a new ammonia production train of 1,000 tpd. Like the first phase, considering the available electrical supply, the optimal annual ammonia production of the additional train is 320 kt NH3/year, so the overall system production would reach 640 kt NH3/year.

The addition of the new ammonia production train entails an increase in electrical generation capacity, electrolysis, compression and storage, BESS, and air separation unit capacities.

The project expansion in 2035 considers increasing the capacity of the PV plant to 1.29 GW. To provide enough electricity during the night, when there is no solar production from the PV plant, the system considers increasing the capacity of two different supply sources: the BESS by 13.6 MWh, with a 6.8 MW inverter, which stores electricity during solar hours, and also a renewable *take-or-pay* PPA for nighttime, increasing its capacity by 22.4 MW due to the addition of the new ammonia production train. This additional capacity is available during low or no solar production hours, i.e., from 18:00 to 6:00 the following day.

For the hydrogen production required by the new ammonia production train, an 806 MW alkaline electrolysis plant is considered, producing hydrogen at 30 bar. A hydrogen storage system at 200 bar is included, with a storage capacity of 103 t H2. A hydrogen reciprocating compressor with a capacity of 9.9 MW, capable of compressing 7.9 t H2/h for storage, is used at this pressure. For nitrogen production, a 34.3 t N2/h cryogenic air separation unit (ASU) is considered. Ammonia production is carried out in a Haber-Bosch plant using the hydrogen and nitrogen produced in the previously described processes.

The produced ammonia is sent via pipeline to the Mejillones Port Complex, where it is stored for later export to the Rotterdam port. It is assumed that ammonia storage and port services are provided by a third party, maintaining the port tariff at 42.7 USD/t NH3. Export is done using Supramax vessels, with a storage capacity of 50 kt of ammonia per vessel, like the first phase of the project.

The table below summarizes the main results of the modeling done for the model plant in both phases, in terms of their production capacities (approximate values):

Parametron	Unit	First Phase (2028)	Second Phase (2035)	Final (2035)
PV Plant Capacity	MW	1,130	1,129	2,259
Nocturnal PPA Capacity	MW	22.1	22.4	44.5
Line Tx 220 k Capacity	MW	1,688	-	1,688
Electrolysis Plant Capacity	MW	803	806	1,609
Hydrogen (H_2) Annual Production	ktpa	56.5	56.5	113
Demineralized Water Consumption (Electrolysis)	m3/year	621,280	621,280	1,242,560
BESS Capacity	MWh/MW	23.5/11.7	13.6/6.8	18.5
Compression 30/200 bar System Capacity	tH_2/h	7.8	7.9	15.7
Air Separator (N_2) Plant Capacity	t H_2	105	103	208
O_2 Total Production (Electrolysis y ASU)	t N_2/h	34.3	34.3	68.6
Cooling Capacity	ktpa	533	533	1,066
Industrial Water Consumption	Termic MW	321	301	622
Ammoniac Plant Capacity (NH_3)	m^3/año	2,215,349	2,215,350	4,430,699
Load factor of the Ammonia Plant (NH_3)	t NH_3/h	41.7	41.7	83.3
Annual production of Ammoniac	%	87.7	87.6	87.7
	kpta	320	320	640

Table 7. Modeling Results.
Source: (Hinicio, 2023)

The conceptual design with its sizing is the result of a systemic optimization model, which depends on the assumptions used. As the engineering development progresses in the subsequent phases of the project, it will be necessary to review and update the assumptions and parameters to continue deepening the optimization.

4.3 Cost estimation

4.3.1 Capital expenses of the system

For the model plant configuration, an investment cost (CAPEX) of approximately 2,000 MUSD was estimated for phase 1. The main investment costs correspond to the electrical supply and hydrogen production and storage, covering about 70% of the total investment costs, as shown in the following figure.

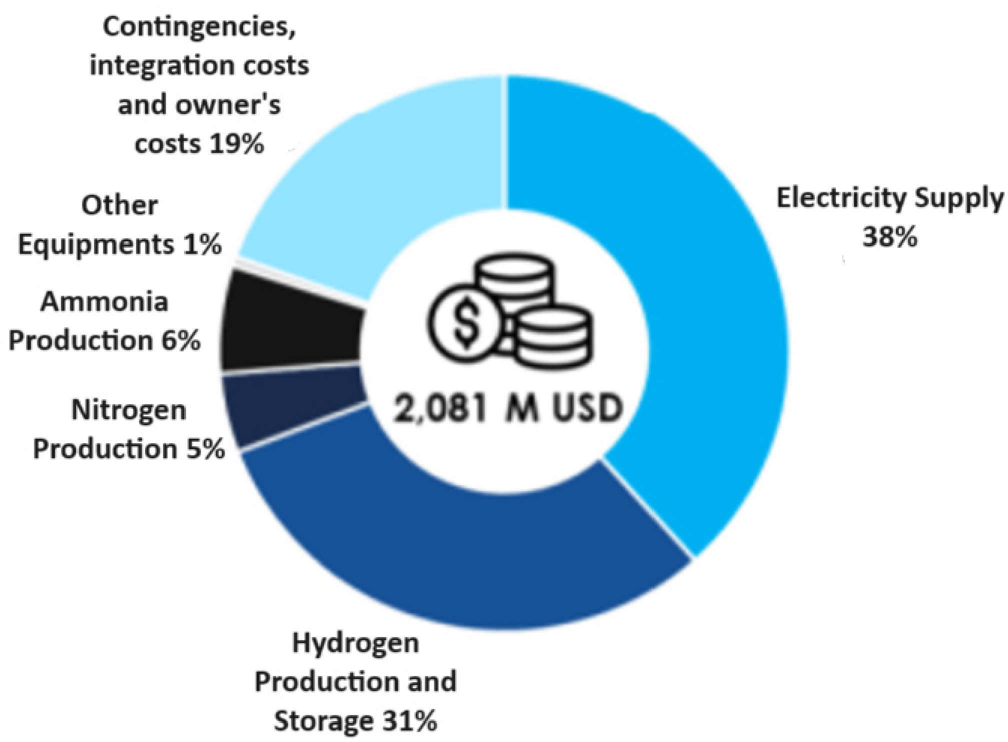


Figure 38. CAPEX for the first phase of the model plant.

Source: (Hinicio, 2023).

The investment costs for each component considered within the system are presented in the following table:

System	Capacity		Cost (MUSD)	%
PV Plant	1.13	GW	677	33%
Tx 220 kV Line	1.69	GW	77	4%
Substation 220/33 kV	1.69	GW	38	2%
BESS	23.5 (10.1)	MW (MWh)	7	0%
Electrolysis Plant	803	MW	534	26%
Compression System 30/200 bar	7.8	t $H_{2/h}$	12	1%
H2 200bar Storage	105	t H_2	95	5%
Air Separation Unit (ASU) (N_2)	34.3	t N_2/h	95	5%
Ammoniac Plant (NH3)	41.7	t NH_3/h	130	6%
Cooling System	321	MWtherm.	11	1%
Owner's Costs			84	4%
Integration Costs			100	5%
SUBTOTAL			**1,859**	**89%**
Contingencies			222	11%
TOTAL			**2,081**	**100%**

Table 8. CAPEX for each subsystem for the first phase of the project.

Source: (Hinicio, 2023)

For this second phase, the total CAPEX of this phase is 19% lower than the first phase, due to the decrease in the electrolyzer and PV plant CAPEX, as well as not considering the investment in electrical infrastructure for electricity transmission, which was already completed in the first phase.

4.3.2 Operating costs

Operating costs (OPEX) were estimated for the entire value chain, including maritime transport costs to the Port of Rotterdam. Thus, the OPEX for the first year of operation of the first phase of the project is approximately 90 MUSD.

The highest contribution to OPEX, at 16.5% of the total, comes from port fees, including the cost of ammonia storage and transfer, as well as pipeline transport from the production plant to the port. The subsystem with the highest OPEX is the PV plant at 16.4% of the total, followed by the electrolysis plant at 16.1%. Costs associated with industrial water consumption, maritime transport of ammonia from Mejillones to Europe, and the use of nighttime PPA represent 10.7%, 10.4%, and 9.4% of the total OPEX in 2028, respectively. OPEX associated with subsystems such as the transmission line, substation, BESS, staff costs, among others, represent a smaller proportion of the total.

The highest OPEX occurs in the last year of system operation, in 2057, at 98.8 M USD. The fraction represented by the PV plant and the electrolysis plant decreases compared to the OPEX of the first year of operation, at 13.7% and 13.5%, respectively. Due to the degradation of the PV plant and the electrolysis plant's cell stack, more energy and consequently, cooling are required, resulting in increased water and energy requirements.

4.3.3 Levelized costs

Based on the estimates, the LCOA was calculated, resulting in a value of 928 USD/t NH3 for the first phase, where 71% of the value corresponds to CAPEX and 29% to OPEX. Figure 39 shows a breakdown of the LCOA according to its different components.

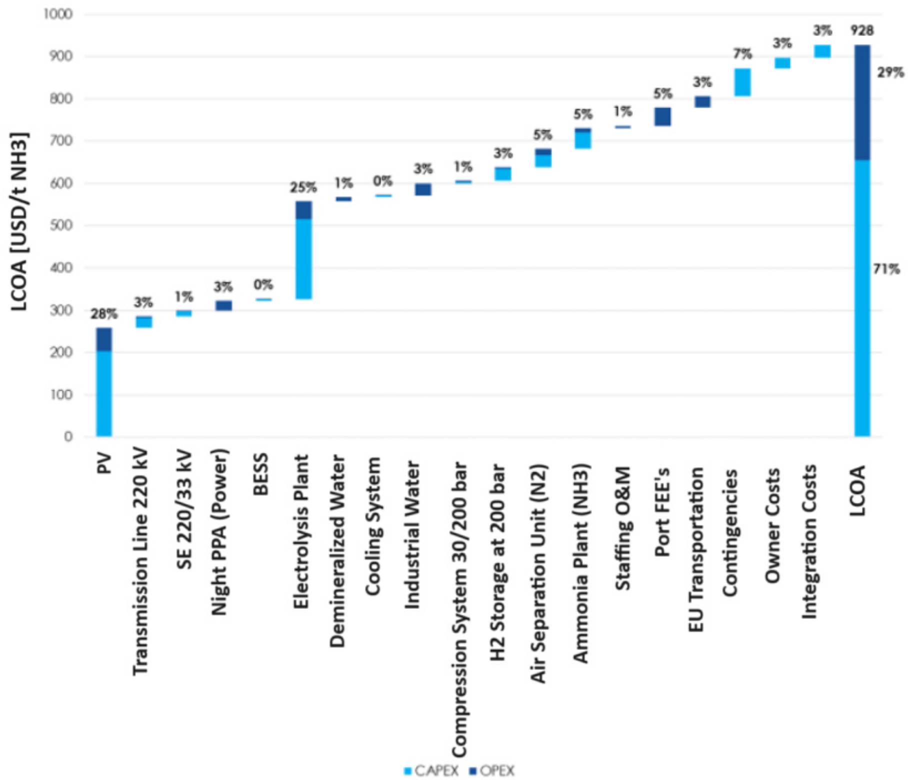


Figure 39. Distribution of the levelized costs of the ammonia plant.

Source: (Hinicio, 2023).

The PV plant and the electrolysis plant are the systems that have the most influence on the LCOA, representing 28% and 25%, respectively. Other systems that have a considerable influence, although much lower than the plants, are the ASU and the ammonia plant, each representing 5% of the LCOA. Contingencies, owner costs, and integration costs represent 13% of the LCOA.

The port fee of 42.7 USD/t NH3 has a 5% impact on the LCOA. Shipping to the port of Rotterdam from the Mejillones Port Complex incurs a cost of 26.9 USD/t NH3, contributing 3% to the LCOA. This transportation results in emissions of 16.8 kg CO2/t NH3 transported, considering Supramax vessels with 50 kton ammonia storage. The FOB LCOA of the project's first phase, i.e., excluding maritime transportation, is 901 USD/t NH3. The levelized cost of ammonia, grouped in major production areas, is presented below:

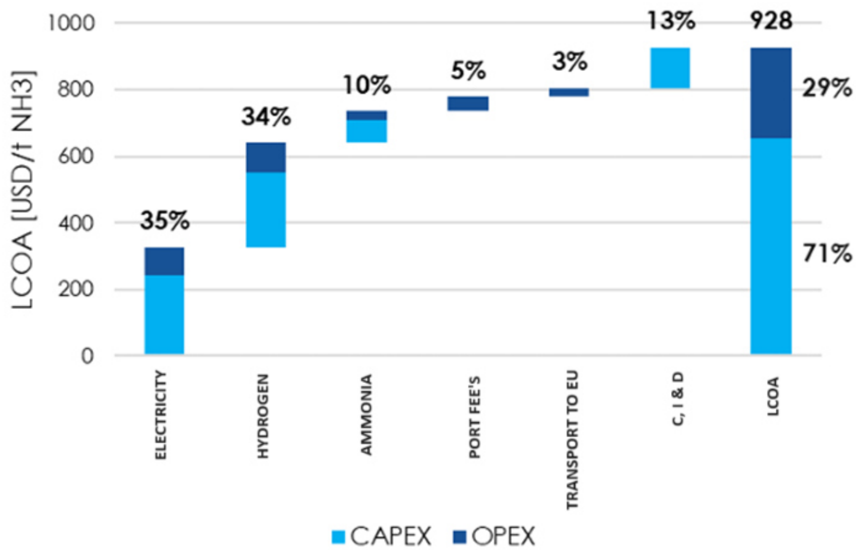


Figure 40. Aggregated levelized costs of ammonia.[10]

Source: (Hinicio, 2023).

Electric supply is the area that has the greatest influence on the levelized cost of ammonia, contributing 35% to the LCOA. Hydrogen production represents a similar percentage to electric supply, contributing 34% to the system's LCOA, while ammonia production (ASU and HB) represents only 10% of the LCOA. As mentioned earlier, the Port Fee and shipping to the Port of Rotterdam represent 5% and 3%, respectively.

For the second phase of the project, an LCOA of 789 USD/t NH3 is obtained due to a presumed 19% decrease in the electrolyzer and PV plant CAPEX, as well as not requiring additional electrical infrastructure installation for transmission. Considering both phases, the final LCOA of the project is 836 USD/t NH3. The following table shows the results of the cost evaluation obtained based on the model. For more details on the levelized cost of electricity (LCOE) and levelized cost of hydrogen (LCOH), see Annex 4 of the present Report.

Results	FIRST PHASE 2028	SECOND PHASE 2035	TOTAL 2035
Levelized Cost of Electricity (USD/MWh)	35.0	27.9	32.6
Hydrogen Levelized Cost (USD/kg H_2)	4.1	3.3	3.6
Ammoniac Levelized Cost (USD/ t NH_3)	928	789	836
Total CAPEX or Total Investment Cost (MUSD)	2,081	1,684	3,765

Table 9. CAPEX y and levelized costs.

Source: (Hinicio, 2023).

[10] C, I, and D correspond to contingency costs, integration costs, and owner costs, respectively.

To understand the variables that have the most impact on the final LCOA value, while keeping all equipment capacities fixed, a sensitivity analysis was conducted, concluding that the electrolyzer CAPEX, discount rate, and PV plant CAPEX are the factors with the most impact.

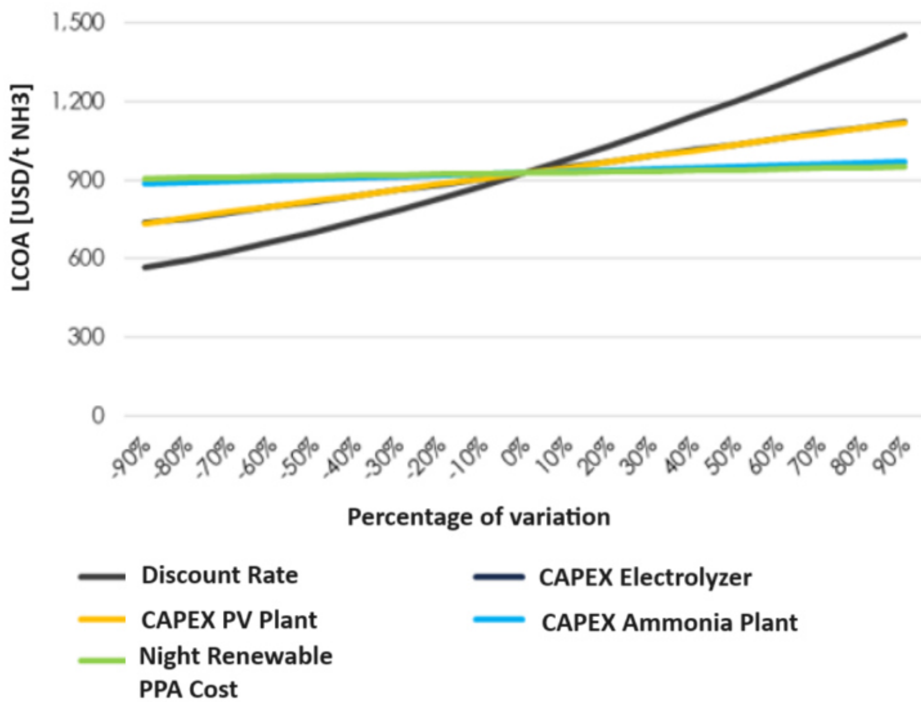


Figure 41. Sensitivity analysis of the levelized costs of green ammonia.

Source: (Hinicio, 2023).

Based on the previous results, some conclusions can be drawn to guide optimization efforts of the value chain in the following stages of project development:

- Increasing the electrolyzer capacity factor has a very relevant impact on production costs, so all possible measures should be sought to achieve this effect.
- Reducing the technical minimum operation of the Haber Bosch plant (below 30%) can also have a significant impact, as it allows for a reduction in hydrogen storage and higher costs of block energy at night. This reduces the upstream plant sizing since a smaller amount of electricity and hydrogen must be produced for use during non-solar hours.
- The highest contribution to H2 and consequently to NH3 costs is from renewable electricity. Therefore, it is recommended to consider adding other sources that can complement the generation profile. The current design considers a supply of renewable energy from a solar profile, which conditions the entire downstream design of the renewable plant, including overcapacity of H2 production, storage systems, and flexibility of the ammonia plant to accommodate this production profile. A renewable PPA at a competitive cost would allow optimizing the design by reducing the renewable/electrolysis ratio, storage systems, and ammonia plant operation.
- The high CAPEX requirements, as well as the impact of the discount rate on levelized production costs, highlight the importance of reducing risk levels for the development of these projects. This refers to both country risk levels, as well as risks inherent in project development, or risks of contracts and financing structures. To be competitive, countries and projects must constantly seek risk reduction strategies for their projects, with significant participation from international investors.

5 Collaboration with stakeholders and results dissemination

To achieve its purposes and develop the proposals outlined in this public-private collaboration project, as well as to continue and make its implementation viable in subsequent phases, collaboration with public and private organizations is of the utmost importance. Based on this understanding, the project was concerned from its inception with consulting and involving different competent public sector actors, as well as trade associations and private companies. Among the project's objectives was also collaboration with academic and research institutions, to contribute to the specialized human capital formation and local research capacity development, aspects that are especially relevant at this stage of developing the new green hydrogen industry.

This chapter describes the initiatives developed for collaboration and involvement of public institutions, academic institutions, and the private sector. Finally, it also mentions the activities carried out to validate and disseminate the project's results in various seminars and conferences during its execution.

5.1 Collaboration with public institutions

According to the governance defined by the Chilean government in the Green Hydrogen Action Plan (see section 1.1 of the present Report) and the project's characteristics, the following institutions are identified as the most relevant for the development of this report:

- Ministry of Energy
- Corporation for Production Development (CORFO)
- Municipality of Mejillones
- Ministry of National Assets
- Regional Government of Antofagasta

From the beginning of the project, contact was sought with different officials from these institutions, both at the local, regional, and national levels. The project's purposes and initial proposals were generally well received by these institutions, with the project committing to share its progress and proposals with the authorities.

During the year 2023, the Ministry of Energy was developing the participatory formulation process of the Green Hydrogen Action Plan 2023-2030, with the purpose of defining and disseminating a "roadmap between 2023 and 2030 that allows the deployment of a sustainable green hydrogen and derivatives industry." In the different instances and working groups at the regional level contemplated in the process, Soventix - representing the PPP project development consortium - actively participated to contribute its industrial park proposal to the elaboration of this Action Plan.

On the other hand, CORFO authorities offered their institutional support for the development of this proposal throughout the project, formally expressing their interest in continuing the Industrial Park development into a next phase of design and implementation. CORFO's support, in its Interministerial coordination role, was also relevant for approaching other ministries, such as the Ministry of National Assets, which manages the fiscal lands that the park would require.

Coordination with the Municipality of Mejillones is of the utmost importance to analyze location alternatives for the industrial park within the communal territory, ensure compatibility with territorial planning instruments, acceptance by local communities, etc. The Municipality was just beginning a process to update its Communal Regulatory Plan, making the analysis with municipal authorities of a development proposal and location of an industrial park relevant.

5.2 Collaboration with the private and financial sector

The proposal for an industrial park makes sense if there are private companies, project developers, that see advantages and have an interest in locating their projects inside it. Therefore, conversations were also initiated from the beginning with project developers in the region to verify their interest. In these conversations, the advantages of shared infrastructure, initial investment reduction, and opportunities to leverage synergies were highly valued. Several presentations were made at trade associations that bring together private companies linked to the green hydrogen industry, both nationally (H2 Chile) and regionally (H2 Antofagasta). Likewise, more than 4 confidentiality agreements (NDAs) were signed with project developers in the region with the purpose of sharing more detailed information about the projects and deepening collaboration initiatives.

In addition to project companies, potential participants in the industrial park, it was important to advance conversations with potential service providers for the projects and the park itself. These types of companies, supplying desalinated water, port and logistics services, renewable energy supply, etc., must also play an important role in the development of an industrial park and the provision of shared infrastructure. Confidentiality agreements (NDAs) were also signed with several of these companies to explore collaboration opportunities in greater depth.

Additionally, conversations were initiated with the financial sector, especially with multilateral institutions, to understand their perspective on the challenges regarding green hydrogen and derivatives projects development in Chile and hear their opinion on the proposal for an industrial park. Meetings were held with executives from the World Bank, International Finance Corporation (IFC), Inter-American Development Bank (IDB), European Investment Bank (EIB), German Development Bank (KfW), and with CORFO executives in charge of developing financing instruments (facility) for projects in this industry.

5.3 Collaboration with academic and research institutions

Regarding this point, one of the objectives of the project was to collaborate with student training and research institutions. To achieve this, contact was made with several Chilean and German universities from the outset to offer research topics for undergraduate and postgraduate students to carry out their academic projects.

In this context, topics were proposed, and guidance was provided for the thesis work of two engineering students from the Universidad Católica de Chile, the thesis work of a student from the Universidad Adolfo Ibáñez de Santiago, and the master's thesis of an international student from the University of Flensburg in Germany, who carried out his work in Chile.

Contact was also made with researchers from the Universidad Católica del Norte in Antofagasta to collaborate on their research on topics related to green hydrogen and regional development, providing information, and creating links with German universities. Active collaboration was also sought with an applied technology research center (CICITEM), exchanging information, and attending joint seminars.

Additionally, an opportunity for collaboration was sought and opened with the University of Munich, with the TUM International GmbH center, with which a joint proposal was developed for an H2-Uppp collaboration project to develop the design and implementation strategy of the Industrial Park, which would continue as the next stage of this work (see also Recommendations section).

5.4 Communication of results

The following are the national and international events where the main results of this project were presented and communicated:

1. <u>**First Congress of Green Hydrogen Projects Developers in Antofagasta**</u>

Organized by the H2 Antofagasta Guild Association on 04/21/2023, Auditorium of Aguas Andinas, Antofagasta.
Moderator (Jorge Taboada) of the panel: "Mejillones, opportunities and challenges to become a hub for the export of green hydrogen and its derivatives."

2. World Hydrogen & Renewables Italy
Organized by World Hydrogen Leader, May 2-4, 2023, Rosa Grand Milan, Italy
Speaker (Thomas Stetter) participant in the panel: "Hydrogen imports from North Africa and beyond."

3. Chilean-German Forum: German technologies for the development of the Green Hydrogen Economy.
Organized by the Chilean-German Chamber of Commerce and Industry (AHK) and Mittelstand Global on 05/09/2023, Santiago, Chile.
Speaker (Jorge Taboada) in Block III, H2Uppp Informational Event: topic "Solar NH3-Pool Chile: Optimized green ammonia production pool in Antofagasta for export."

4. Hyvolution: a world of hydrogen
Conferences, exhibitions, and B2B meetings, organized by H2 Chile, Fisa, and GL events, June 28-30, 2023, Santiago, Chile.
Speaker (Jorge Taboada) in panel 3: "Shared infrastructure."

5. 5th Green Hydrogen Summit-Chile LAC 2023
Conferences, exhibitions, and B2B meetings, organized by GIZ and CORFO, October 25-26, 2023, Santiago, Chile.
Speaker (Jorge Taboada) in panel 4: "Shared infrastructure for the industry."

6. European Hydrogen Week 2023
Side Event "*Chile: Current Hydrogen Projects and Business Opportunities*", organized by GIZ, on November 21, 2023, in Brussels, Belgium.
Speaker (Thomas Stetter): "Solar Ammonia Chile Project."

7. World Hydrogen Latin America
Conferences, exhibitions, and B2B meetings, organized by, December 12-14, in Santiago, Chile.
Speaker (Jorge Taboada) of the Case Study, Project "Solar Ammonia Chile": Optimization of the green ammonia value chain.

8. Seminar in Antofagasta: "Conditions for the Competitiveness and Sustainability of the Green Hydrogen and Derivatives Industry in Antofagasta."
Closing event of the H2Uppp Project and dissemination of the main results, organized by GIZ and Soventix, with the collaboration of the German Chamber of Commerce in Chile (AHK), H2 Antofagasta, and the Universidad Católica del Norte, on January 24 at the Universidad Católica del Norte, Antofagasta, Chile.

6 Conclusions and recommendations

6.1 Conclusions

The public-private collaboration project, within the H2Uppp program of GIZ, has developed the foundations for developing an industrial park in Mejillones, which would improve the competitiveness and sustainability of the emerging green hydrogen and derivatives industry in the Antofagasta region. By facilitating the use of shared infrastructure and the efficient use of economies of scale and scope, reducing initial investments and development risks, the projects located within the industrial park will have competitive advantages, thus also increasing the international competitiveness of the Antofagasta region.

It should be noted that it is not enough to take advantage of the excellent renewable energy resources of the region or to optimize the design of industrial plants; it is also necessary to create institutional and public policy conditions, as seen in other international experiences, that allow Chile and Antofagasta to position themselves advantageously in the international competition for the large investments needed to develop this industry. The proposal to develop an industrial park in Mejillones aims to contribute to this regard.

The advantages for a private project to be located within the proposed industrial park in Mejillones are multiple. In this work, several **qualitative** advantages were proposed, given the conceptual stage of development of the proposal:

- More expedited access to land in a planned area.
- Lower environmental and community risks.
- Shorter timelines for obtaining permits.
- Lower development and financing risks.
- Access to service companies and equipment suppliers that are installed in the industrial park.

There are also other advantages, for which some **quantitative** estimations have been presented, which can be used as guides for location decisions, such as:

- In the case that a project does not have shared infrastructure and must build its own port and storage facilities, the project's CAPEX would increase by at least 200 million dollars.
- If a project must build its own desalination plant, the project's CAPEX would increase by approximately 8 million dollars.
- If two or more projects can share a dedicated transmission line or relevant sections, they could reduce the CAPEX of their electrical transmission systems by up to 40%.
- If road and railway access to projects are resolved in an industrial park, investments in this high-cost infrastructure are significantly reduced.

On the other hand, the planned industrial park will facilitate territorial planning and help mitigate the negative environmental impacts of projects. Indeed, the green hydrogen and derivatives industry is intensive in its use of land, since the generation of renewable energy (solar and wind) in large volumes also requires large land extensions. To reduce the negative impacts of land use, long-term territorial planning is essential.

The proposal for a long-term master plan for the development of an industrial park allows for orienting the location of industrial plants in the territory, avoiding the fragmentation derived from spontaneous and unplanned locations. It also facilitates the identification of large areas for the development of renewable energy generation plants and the definition of infrastructure corridors, mainly transmission and pipeline lines, to avoid territory fragmentation generated by this linear infrastructure when it develops in an uncoordinated and unplanned manner.

The experience in the municipality of Mejillones over the last decades highlights the territorial problems that can be generated by an inorganic industrial development. For example, inefficient occupation of the coastal edge can be observed in the municipality, as well as territorial fragmentation caused by numerous high-tension lines crossing it. Adequate territorial planning for industrial development and its enabling infrastructure can help overcome these problems, also reducing negative environmental impacts, and improving the image and acceptance by the involved local communities.

The master plan for developing an industrial park is thought to be an instrument that could contribute concretely to that direction. The development of a new industry, which promises to contribute to the decarbonization of the planet and regions, offers an opportunity to learn from past experiences in Antofagasta, implementing new models of industrial development.

The proposal for an industrial park of this nature in Mejillones has been consulted on from its inception and has been well received by public bodies at the different local, regional, and national levels. Collaboration is key at this early stage of industry development, requiring joint work between public and private actors to improve project and country competitiveness and sustainability conditions.

The present report also developed the conceptual design of a green ammonia production plant model. The intention of this design was to identify some of the benefits of a private project being located within the industrial park. Using a systematic approach to optimizing the complete value chain, this design allowed estimating the CAPEX and OPEX of the model plant and thus the levelized costs of hydrogen (LCOH) and ammonia (LCOA) production. The design contemplates project development in two stages, to take advantage of economies of scale in the ammonia synthesis processes.

The first stage contemplates a production capacity of 1,000 tons/day (320 kton/year equivalent), with a doubling of capacity in the second stage reaching 2,000 tons/day. For the first stage, a total investment cost (CAPEX) of approximately 2,000 million USD was estimated, considering investments for the entire required capacity of renewable energy supply and transmission systems. Regarding operational costs (OPEX), the costs of the complete value chain were estimated, including maritime transport costs to the Port of Rotterdam. For the first year of the project, an operating cost of 86 million USD was estimated, and for the last year, a higher one of 99 million USD, due to the additional energy required due to the degradation of the photovoltaic plant and the electrolysis stack.

On the other hand, the results obtained in the evaluations are positive in relation to the project objectives, due to the possible achievement of levelized costs of ammonia production (LCOA), which are competitive compared to average international market prices of gray ammonia. If contributions from additional income flows of the project, such as the commercialization of by-products (oxygen, surplus renewable energy, sale of carbon credits) are considered, production costs (LCOA) in the range of 600 to 800 USD/ton of ammonia can be reached, with levelized hydrogen costs (LCOH) in the range of 3.5 to 4.0 USD/kg.

These values are compared with an average international market price of NH3 of around 500 USD/ton in the last 10 years, showing its volatility since 2021, with highs of up to 1,600 USD/ton. In this context, it is concluded that a stable long-term price for green ammonia, 20% to 60% higher than the current average market price of gray ammonia, is a promising result, as it is a higher-quality substitute product by significantly reducing greenhouse gas emissions in its value chain. Regarding the competitiveness of the LCOA results obtained, it can be affirmed that they are within the range of the lowest costs estimated by IRENA for renewable ammonia, which currently indicates possible values of 720 USD/ton in regions with the best renewable energy resources, considering a CO2 price of approximately 150 USD/ton as a contribution to reducing the production cost of renewable ammonia (IRENA, 2022).

Regarding the contributions of a green ammonia plant to decarbonization objectives, the study concludes that with a production in the first stage of the model plant of 320,000 ton/year, CO2 emissions are reduced by approximately 600,000 tons/year.

Considering the results of this project under the H2Uppp program, the consortium members that developed it decided to establish a joint-stock company called *Solar Ammonia Chile SpA*, incorporating 2 other partners, with the purpose of continuing to develop a green ammonia production project in the Antofagasta Region.

6.2 Recommendations

This work developed a master plan for the development of an industrial park in Mejillones. To advance its materialization, detailed designs of the different aspects mentioned below are required, as well as the development of a specific strategy for its implementation.

The need to define, together with the competent public bodies and using the most effective instruments, a strategic land reserve area for the long-term development of the industrial park should be emphasized. This definition must be timely to provide clear signals to the market and guide the location/investment decisions of private industrial projects in the short term before they determine independent and disjointed positions. Collaboration of all involved public actors is key in this regard (e.g., National Assets, CORFO, Regional Government), as well as public-private collaboration (e.g., private project developers).

Another aspect that should be prioritized is the design of a governance structure for the industrial park that is compatible with the relevant legal and regulatory framework and assumes the functions of park and infrastructure management. It is necessary to have an entity responsible for management, coordinating the participation of the different public and private organizations involved in park development, being responsible for the implementation of the master plan, acting as the holder to manage all required permits, developing effective business models, and structuring financing to provide the park with minimum urbanization and infrastructure (access, structuring roads, security), etc.

For the implementation of the industrial park, it is also necessary at this stage to make a strategic assessment of the economic, social, and environmental impacts that its development would have. A clear and detailed vision is required regarding the contributions of the industrial park to local economic development, according to its connections and possible productive diversification, its contributions to local and regional decarbonization, its positive and negative impacts on nearby communities, and the most significant environmental aspects to consider in the designs. This will be the basis for developing a sustainable long-term implementation strategy, integrating all aspects, and having the necessary support from authorities and the involved communities.

In this context, it is recommended to continue the work started with this project, moving to a second stage of detailed design, which includes what was mentioned in the previous paragraphs, to advance in the short term towards effective implementation. This proposal is consistent with the Green Hydrogen Action Plan 2023–2030 and has the institutional support of CORFO with a support letter. For this stage, it is pertinent to consider as a reference the guidelines developed by the United Nations Industrial Development Organization (UNIDO, 2021) for the design of Industrial Eco-parks. This reference framework provides an international standard for design, incorporating aspects of governance and circular economy, with the purpose of improving the performance, sustainability, and inclusivity of the industrial sector. These aspects are considered especially relevant for the success of the proposal for an industrial park in Mejillones, providing innovative and differentiating attributes compared to historical experiences of industrial development in the municipality.

Finally, it should be noted that an industrial park like the one proposed for green hydrogen and derivatives projects offers great added value to improve the country's attractiveness to international investors. In Antofagasta, as argued in this work, this is easier than in other regions that do not have the same industrial development and enabling infrastructure. However, it is thought that this proposal has interesting potential to be replicated in other regions of the country and even internationally, adapting it to their specific conditions.

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Annex 1

1. Regulations regarding the handling of ammonia and hydrogen

Regulation	Responsible Entity	Description
Decree 43/2016	Ministry of Health	Regulation on the storage of hazardous substances.
Decree 594/2000	Ministry of Health	Regulation on basic health and environmental conditions in workplaces.
Resolution 408/11-MAY-2016	Ministry of Health	List of hazardous substances to health.
Decree 298/1995	Ministerio de Transporte y Telecomunicaciones	Regulation on the transportation of dangerous goods by streets and roads.
Resolution 96/1997	Ministerio de Transporte y Telecomunicaciones	Regulation on the handling and storage of dangerous goods in port facilities.
Decree 40/1969	Ministerio de Trabajo y Previsión Social	Regulation on the prevention of occupational risks.
Decreto 132/2004	Ministry of Energy	Regulation on mining safety.
NCh 382 Of. 98	INN	Classification of dangerous goods.
NCh 2190 Of. 2003	INN	Transport of dangerous substances.
NCh 1411/4 Of. 78	INN	Safety signs for the identification of material risks.
NCh 2245 Of. 2015	INN	Safety data sheet for chemical products.
Law 21305/2021	Ministry of Energy	Defines hydrogen as a fuel.
Decree 13/2022	Ministry of Energy	Regulation on the safety of hydrogen installations and amendments to the gas installers regulation.

2. Regulations regarding land disposition and construction of industrial premises

Regulation	Responsible Entity	Description
Decree 47/1992	Ministry of Housing and Urban Development	Establishes a new general text of the general law of urbanism and construction.
Resolution 73/2004	Regional Government Region of Antofagasta	Intercommunal Regulatory Plan of the Coastal Edge.
Ordinance 33/2000	Mejillones Municipality	Communal Regulatory Plan of the Port and Bay of Mejillones.
Decree 445/ 2013	Mejillones Municipality	Modification of the Communal Regulatory Plan of Mejillones.
Decree 2150/2017	Mejillones Municipality	Rectifies amendment to the Communal Regulatory Plan of Mejillones.

3. Legal frameworks related to environmental assessment

Regulation	Responsible Entity	Description
Law 19300/1994	Ministry General Secretariat of the Presidency.	Law on General Bases of the Environment.
Law 20417/2010	Ministry General Secretariat of the Presidency.	Amends Law 19.300.
Law 21455/2022	Ministry of the Environment	Framework Law on Climate Change
Decree 40/2013	Ministry of the Environment	Regulation of the environmental impact assessment system.
R.E. 1.518/2013	Ministry of the Environment	Establishes the obligation to provide the Environmental Evaluation Service (SMA) with the data declared in the RCA.

R.E. 885/2016	Ministry of the Environment	General Standards on Reporting Duties for Notices, Contingencies, and Incidents through the Environmental Monitoring System.
Ley N° 20.920/2016	Ministry of the Environment	REP Law (Extended Producer Responsibility)
D.S. 1/2013	Ministry of the Environment	Regulation of the Emissions and Pollutant Transfer Registry (RETC).
D.S. Nº 148/2003	Ministry of Health	Sanitary Regulation on Hazardous Solid Waste Management.
D.S. N°43/2016	Ministry of Health	Regulation on the Storage of Hazardous Substances.

4. Support guides for the authorization request of special green hydrogen projects

Guía	Área
ASME B31.12 Hydrogen piping and pipelines.	General to the value chain
CSA B51 Boiler, Pressure Vessel, and Pressure Piping Code.	General to the value chain
NFPA 2 caps. 1 a 8 General, CH2 y LH2.	General to the value chain
ASME SPT-PT.006 Design Guidelines for hydrogen Piping and Pipelines.	General to the value chain
ISO 14687 Hydrogen fuel quality – Product specification	General to the value chain
NFPA 55 Compressed Gases and Cryogenic Fluids Code	General to the value chain
NFPA 2 capítulo 13 Hydrogen Generation Systems	H2 Production
ISO 16110 Hydrogen generators using fuel processing technologies	H2 Production
ISO 22734 Hydrogen generators using water electrolysis – Industrial, commercial and residential applications	H2 Production
ANSI/CSA HGV 4.8 – 2012 (R2018) Hydrogen gas vehicle fueling station compressor guidelines	Conditioning
ASME (BPVC) Boiler and Pressure Vessel Code	Storage
EIGA 100/11 Hydrogen Cylinders and Transport Vessels	Storage
NFPA 2 cap. 7 Gaseous Hydrogen	Storage
ISO 16111 Transportable gas storage devices – Hydrogen abosrbed in reversible metal hydride	Storage
CGA H-2 Guideline for Classification and Labeling of Hydrogen Storage Systems with Hydrogen Absorbed in Reversible Metal Hydrides	Storage
EIGA 171/12 Storage of Hydrogen in Systems Located Underground	Storage
NFPA 2 cap. 8 Liquefied Hydrogen	Storage
ASME B31.12 Hydrogen piping and pipelines	Transport
EIGA 121/14 (CGA G-5.6) Hydrogen Pipeline Systems	Transport
EIGA 06/19 Safety in storage, handling and distribution of liquid hydrogen	Transport
EIGA 15/06 Gaseous Hydrogen Stations Directiva 2008/68/CE, 49 C.F.R. §171 a 180	Transport
ISO 14687 Hydrogen fuel quality - Product specification	H2 Quality
IEC 62282 Fuel cell technologies	Fuel Cell
NFPA 2 capítulo 12 Hydrogen Fuel Cell Power Systems	Fuel Cell

5. Regulations for the certification and consideration of green hydrogen in the EU (RED II)

Regulation	Description
Article 7	Calculation rules for the quota of energy from renewable sources.
Article 11	Joint projects between member countries and third countries.
Article 19	Guarantees of the origin of renewable energy sources.
Article 27	Calculation rules for the minimum percentage of renewable energy in the transport sector.
Article 28	Other provisions of renewable energy in the energy sector.

6. Certifications and standards from certifying entities

Ente certificador	Certificación
Breau Veritas	H2 Certification
Tüv Süd	CMS 70
Tüv Süd	Green hydrogen
CertifHy	Green and Low Carbon
ISCC Plus	N/A
REDcert2Chemie	N/A

7. Regulatory work plan for the hydrogen industry (GH2)

Regulation to develop	Value chain	Ministry	Modify / Create
H2 Facility safety	Production and Storage	Energy	Modify
Safety of liquid H2 facilities and other modifications	Production and Storage	Energy	Modify
Mining safety regulations	Production and Storage	Minery	Modify
Storage of hazardous substances	Production and Storage	Health	Modify
Transport of dangerous goods on public roads	H2 Transport	Transport	Modify
Safety, transport, and distance of gas (H2 + GN) from the network	H2 Transport	Energy	Modify
Gas quality standard (H2 + GN)	H2 Transport	Energy	Create
Safety, transport, and distribution of gas (H2) from the network	H2 Transport	Energy	Modify
Requirement for handling and storage in ports	H2 Transport	Transport	Modify
Safety in handling explosives in ports	H2 Transport	Transport	Modify
Technical standards, quality, and control of fuels	General H2	Energy	Create
Incorporation of H2 as a fuel	General H2	Energy	Modify
Aspects of H2 marketing (DS 132)	General H2	Energy	Modify
Health and environmental conditions in workplaces	General H2	Health	Modify
Gas installers	General H2	Energy	Modify
H2 dispensing stations	H2 Use Applications	Energy	Create
Multi-fuel dispensing stations	H2 Use Applications	Energy	Create
Regulation for homologation certificates	H2 Use Applications	Transport	Create
Fuel cell retrofit	H2 Use Applications	Transport	Modify
Vehicle technical inspection	H2 Use Applications	Transport	Modify
Regulation to LGSE	H2 Use Applications	Energy	Modify
Regulation Mod. DS 125	H2 Use Applications	Energy	Modify
Regulation Mod. DS 52	H2 Use Applications	Energy	Modify

Annex 2

The present Annex includes complementary information to Chapter 2 - Enabling Infrastructure in Antofagasta and Mejillones.

Regarding existing energy generation infrastructure in the Antofagasta region, it amounts to 4.34 GW. Table 1 records the installed capacity of each project, also distinguishing their owners, the type of power plant, the installed capacity, and the municipality associated with the project's location in the region.

Project Name	Owner Name	Municipality	Type of Power Plant	Power (MW)
PFV FINIS TERRAE	ENEL GREEN POWER CHILE S.A.	MARÍA ELENA	SOLAR	248
PFV SOL DEL DESIERTO	PARQUE SOLAR FOTOVOLTAICO SOL DEL DESIERTO	MARÍA ELENA	SOLAR	230
PFV ANDES SOLAR II-B	ANDES SOLAR II SPA	ANTOFAGASTA	SOLAR	207
PFV DOMEYKO	ARCADIA GENERACIÓN SOLAR S.A.	ANTOFAGASTA	SOLAR	207
PE CERRO TIGRE	AR CERRO TIGRE SPA	ANTOFAGASTA	WIND	185
PFV COYA	ENGIE ENERGÍA CHILE S.A.	MARÍA ELENA	SOLAR	181
PFV SANTA ISABEL	TSGF SPA	ANTOFAGASTA	SOLAR	170
PE LLANOS DEL VIENTO	AR LLANOS DEL VIENTO SPA	ANTOFAGASTA	WIND	160
PE TCHAMMA	AR TCHAMMA SPA	CALAMA	WIND	158
PFV VALLE DEL SOL	ENEL GREEN POWER CHILE S.A.	MARÍA ELENA	SOLAR	153
PE CALAMA	ENGIE ENERGÍA CHILE S.A.	CALAMA	WIND	153
PFV SOL DE LILA	ENEL GREEN POWER CHILE S.A.	ANTOFAGASTA	SOLAR	152
PFV BOLERO	HELIO ATACAMA TRES SPA	SIERRA GORDA	SOLAR	138
PFV TAMAYA SOLAR	ENEGIE ENERGÍA CHILE S.A.	TOCOPILLA	SOLAR	115
CSP CERRO DOMINADOR	CERRO DOMINAR CSP S.A.	MARÍA ELENA	CONCENTR ATED SOLAR POWER	114
PE SIERRA GORDA ESTE	ENEL GREEN POWER CHILE S.A.	SIERRA GORDA	WIND	112
PFV SAN PEDRO	GPG SOLAR CHILE 2017 SPA	CALAMA	SOLAR	104
PFV CONEJO SOLAR	CONEJO SOLAR SPA	TAL TAL	SOLAR	104
PFV PAMPA TIGRE	AR PAMPA SPA	ANTOFAGASTA	SOLAR	103
PFV CERRO DOMINADOR	CERRO DOMINADOR CSP S.A.	MARÍA ELENA	SOLAR	100
PE TALTAL	ENEL GREEN POWER CHILE S.A.	TAL TAL	WIND	99
PFV NUEVO QUILLAGUA	PARQUE FOTOVOLTAICO NUEVO QUILLAGUA SPA	MARÍA ELENA	SOLAR	97
GEO CERRO PABELLÓN	GEOTERMICA DEL NORTE SA.	OLLAGÜE	GEOTHERM AL	95

PFV CAPRICORNIO	ENGIE ENERGÍA CHILE SPA	ANTOFAGASTA	SOLAR	90
PE VALLE DE LOS VIENTOS	ENEL GREEN POWER CHILE S.A.	CALAMA	WIND	90
PFV ANDES SOLAR II	ANDES SOLAR II SPA	ANTOFAGASTA	SOLAR	87
PFV PAMPA SOLAR NORTE	ARCADIA GENERACIÓN SOLAR S.A.	TALTAL	SOLAR	69
PFV MARIA ELENA	GENERACIÓN SOLAR SPA	MARÍA ELENA	SOLAR	68
PFV ELENA	SOLAR ELENA SPA	MARÍA ELENA	SOLAR	67
PFV AZABACHE	ENEL GENERACIÓN CHILE S.A.	CALANA	SOLAR	60
PFV USYA	ACCIONA ENERGÍA CHILE HOLDINGS S.A.	CALAMA	SOLAR	56
PFV LALACKAMA	ENEL GREEN POWER CHILE S.A.	TALTAL	SOLAR	55
PFV LA CRUZ SOLAR	FOTOVOLTAICA NORTE GRANDE 1	MARÍA ELENA	SOLAR	53
PFV URIBE SOLAR	FOTOVOLTAICA NORTE GRANDE 5 SPA	ANTOFAGASTA	SOLAR	53
PFV JAMA	PLANTA SOLAR SAN PEDRO III SPA	CALAMA	SOLAR	53
PFV ANDES SOLAR	AES ANDES S.A.	ANTOFAGASTA	SOLAR	22
PFV LALACKAMA II	ENEL GREEN POWER CHILE S.A.	TALTAL	SOLAR	17
PFV DE LOS ANDES	FOTOVOLTAICA DE LOS ANDES SPA	ANTOGAFASTA	SOLAR	10
PMGD PFV CKILIR	CE URIBE DE ANTOFAGASTA SPA	ANTOFAGASTA	SOLAR	9
PMGD PFV LOCKMA	CE CENTINELA SOLAR SPA	ANTOFAGASTA	SOLAR	9
PMGD PFV MITCHI	GR RUIL SPA	ANTOFAGASTA	SOLAR	9
PMGD PFV PAINE	PAINE ENERGY SPA	CALAMA	SOLAR	9
PMGD PFV QUETENA	PARQUE SOLAR QUETENA S.A.	CALAMA	SOLAR	9
PMGD PFV TALLADO	ANGAMOS SOLAR SPA	MEJILLONES	SOLAR	9
PMGD PFV CALAMA SOLAR	CALAMA SOLAR 1 SPA	CALAMA	SOLAR	9
PMGD PFV VICTORIA	VICTORIA SOLAR SPA	CALAMA	SOLAR	9
PMGD PFV PUERTO SECO SOLAR	CALAMA SOLAR 2 SPA	CALAMA	SOLAR	9
PFV DEL DESIERTO	FOTOVOLTAICA DEL DESIERTO SPA	ANTOFAGASTA	SOLAR	8
PFV SOL DEL NORTE	FOTOVOLTAICA SOL DEL NORTE SPA	ANTOFAGASTA	SOLAR	8
PMGD PFV ARMAZONES	SAGESA S.A.	ANTOFAGASTA	SOLAR	5
PMGD PFV PARANAL	SAGESA S.A.	ANTOFAGASTA	SOLAR	4
			TOTAL	**4.343**

Table 1: Installed Capacity in the Antofagasta region.
Source: (Coordinador Eléctrico Nacional, 2024)[5]

Current energy generation in Antofagasta includes the operations of thermoelectric power plants. However, according to the decarbonization plan, some have projected and planned their closure. Examples of the closure schedule for coal-fired power plants in Mejillones are shown in Table 2.

Plant	Closure Commitment	Conversion	Owner
Mejillones CTM1	Dec-24	Closure	Engie
Mejillones CTM2	Sept-24	Closure	Engie
ANGAMOS ANG1	Sept-29	Carnot Battery	AES
ANGAMOS ANG2	Sept-29	Carnot Battery	AES
COCHRANE CCH1	NO CLOSURE DATE	No Announcement	AES
COCHRANE CCH2	NO CLOSURE DATE	No Announcement	AES
HORNITOS CTH1	Dec-25	Biomass	Engie
IE1	Dec-25	Conversión to gas	Engie
ANDINA CTA	Dec-25	Biomass	Engie

Table 2: Schedule of closure for coal-fired power plants in Mejillones.
Source: (Ministry of Energy, 2020).

In addition to the existing electricity generation infrastructure, Antofagasta has a network of gas pipelines (see Figure 1). The technical characteristics of these are presented in Table 3.

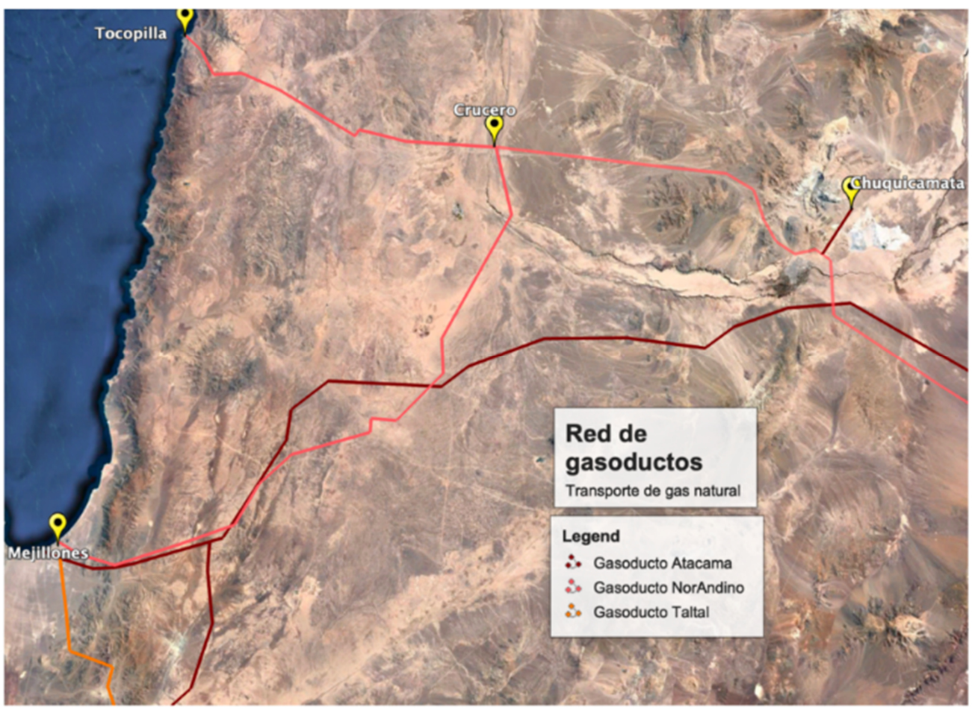

Figure 1: Antofagasta Gas Pipeline Network.Source: Own elaboration.

Gasoducto Zona Norte							
Gasoducto	Tramos	Operador/ Propietario	Diámetro [Pulgadas]	Capacidad [S·M·m^3/día]	Longitud [km]	Material	Máxima presión [Bar]
Gasatacama (internacional)	Cornejo (Salta, Argentina) / Paso de Jama (frontera)	Gas Atacama Chile SA / Enel Generación Chile S.A	20	5,4 Espesor: 0.288'' a 0.423''	530	API 5L X-70	100
	Paso de Jama (frontera) / Mejillones		20	5,4 Espesor: 0.288'' a 0.423''	411		100
Norandino (internacional)	Pichanal (Salta, Argentina) / Paso de Jama (frontera)	Gasoducto Nor Andino S.A. (Nombre comercial, NorAndino)	20	7,1	450	API 5L X-70	100
	Paso de Jama (frontera) / Crucero		20	7,64	260		97,6
	Crucero / Tocopilla		12	1,6	79		100
	Crucero / Quebrada Ordóñez		16	5,5	252		100
	Quebrada Ordóñez / Mejillones		16	3,9	35		100
	Quebrada Ordóñez / Coloso		16	1,6	104		100
Taltal (nacional)	Mejillones / La Negra	Gasoducto Taltal Limitada / Enel Generación Chile S.A.	16	2,4 Espesor: 0.203'' a 0.375''	88	API 5L X-70	99,2
	La Negra / Paposo (Taltal)		12	1,8 Espesor: 0.203'' a 0.375''	141		99,2

Table 3: Gas Pipelines in the Antofagasta Area with their Characteristics.
Source: (GIZ, 2021[11]).

[11] Information available at: https://4echile.cl/publicaciones/inyeccion-de-hidrogeno-en-redes-de-gas-natural/

Annex 3

This Annex includes complementary information to Chapter 02 - Enabling Infrastructure in Antofagasta and Mejillones. In addition to specifying the region's water infrastructure, the Annex includes an economic evaluation of supplying desalinated water for a hydrogen industrial park.

The region also has a water supply network, which is mainly used to meet the water demand of mining operations. (see Figure 1).

Figure 1: Water Supply in the Antofagasta region.
Source: (Suazo,, 2022).

The water crisis in Chile has led to several projects, especially those located in the northern part of the country, opting for the installation of desalination plants to supply water from the sea. Currently, the country has a production capacity of 8,200 liters per second of seawater (ACADES, 2023). According to Table 1, the Antofagasta region has a large current (77% of national capacity) and projected seawater capacity.

Region	Current Capacity			Future Capacity		
	l/s	%	N	l/s	%	N
Operativas	8,558	100	38	38,766	100	76
Tarapacá	12	0.1	1	2,067	5.3	4
Arica	208	2.4	1	408	1.1	2
Antofagasta	6,603	77.1	25	19,591	50.5	32
Atacama	1,620	19.0	4	9,177	23.7	14
Coquimbo	4	0.0	1	3,804	9.8	13
Valparaíso	59	0.7	3	3,669	9.5	8
Biobío	33	0.4	1	33	0.1	1
Aysén	3	0.0	1	3	0.0	1
Magallanes	15	0.2	1	15	0.1	1
Sist. de impulsión sin desalinización			5			5
No operativas			3			3
Sin información			2			2
Proyecto suspendido o fusionado						11

Total		**48**		**97**

Table 1: Distribution of desalination plants in Chile.
Source: (Vicuña et al., 2022).

Green hydrogen production also requires water supply. For every kilogram of hydrogen produced through water electrolysis, between 9 to 12 kilograms of demineralized water are required. Regarding its quality, the water must have a higher degree of purity to prevent mineral deposition and, consequently, the deterioration of electrolyzer components (Vásquez & Salinas, 2019).

Considering the water consumption for green hydrogen production, as well as for ammonia production, it is necessary to develop sustainable water solutions to enable the green hydrogen industry in Chile, especially the proposed industrial park. Therefore, the work included cost estimation and economies of scale of desalination plants.

The analysis included the technical-economic conceptualization of two scenarios of seawater treatment plants. The first one consists of a plant with a productive capacity of 50 ls to supply a green ammonia plant that produces approximately 2,000 tons per day. The second scenario considers a capacity of 500 l/s to supply an industrial park, equivalent to 10 green ammonia production plants with the same production capacity as the one announced in the first scenario (20,000 tons per day).

The analysis showed that, due to economies of scale, the unit production cost of desalinated water decreases as the treated water flow increases (see Table 2), achieving a 25% reduction in unit cost.

Plant Unit Cost 50 l/s	Plant Unit Cost 500 l/s
$2,38	**$1,91**

Table 2: Unit production cost of a 50 l/s desalination plant and a 500 l/s desalination plant.
Source: (Self-generated, 2023).

The decrease in unit production cost is mainly due to the reduction in capital expenditure (CAPEX). However, it is also relevant to consider the operational expenses for operating the water treatment plants, such as the cost associated with electricity consumption. For this purpose, an energy cost of 80 USD/MWh for the day, 150 USD/MWh for the night, and 10 USD/MWh as a network usage toll were considered. It is concluded that the electricity consumption of a desalination plant represents approximately 70% of the operating costs (see Figure 2).

Figure 2: Distribution of operational costs for a 50 l/s plant and a 500 l/s plant.
Source: (Self-generated, 2023).

Finally, through a sensitivity analysis, it is observed that the variable with the greatest impact on the unit production cost of desalinated water is the energy cost, exceeding the investment cost (see Figure 3).

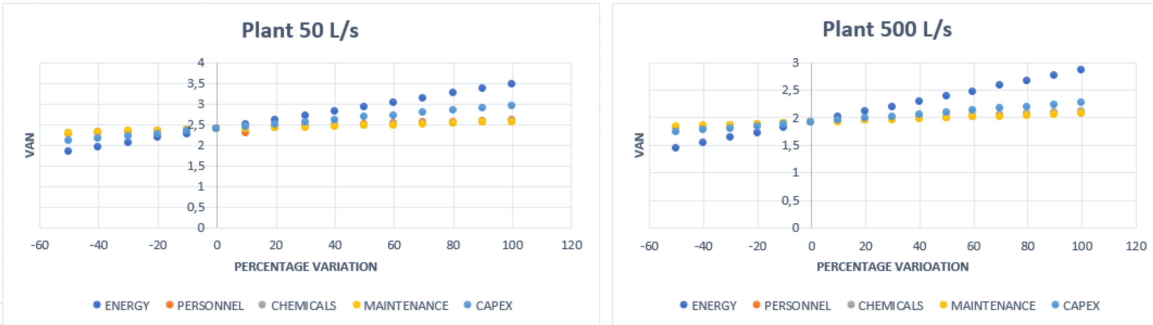

Figure 3: Sensitivity analysis for a 50 l/s desalination plant and a 500 l/s desalination plant.
Source: (Self-generated, 2023).

In conclusion, individual green hydrogen and derivative projects can economically benefit from an industrial park if they take advantage of the synergies of sharing a desalination plant. The benefit is enhanced in regions where the cost of renewable energy is lower, such as in Antofagasta.

Annex 4

- **LCOE**

The levelized cost of electricity (LCOE) for the first phase of the project is 35 USD/MWh, with the PV plant being the system that has the greatest influence on the LCOE, contributing 67% of it. Other systems that have a considerable influence on the LCOE are the oversized transmission line for a second phase and the 22.1 MW renewable nighttime PPA, each representing 7% of the system's LCOE. To compensate for the degradation of both the PV plant and the electrolysis stack (which is replaced every 10 years), the system considers an additional cost associated with the additional consumption required to compensate for the degradation. This consumption has a unit cost equivalent to the levelized cost of electricity, and the total cost associated with this consumption represents 4% of the LCOE.

77% of the LCOE corresponds to CAPEX, while the remaining 23% corresponds to OPEX.

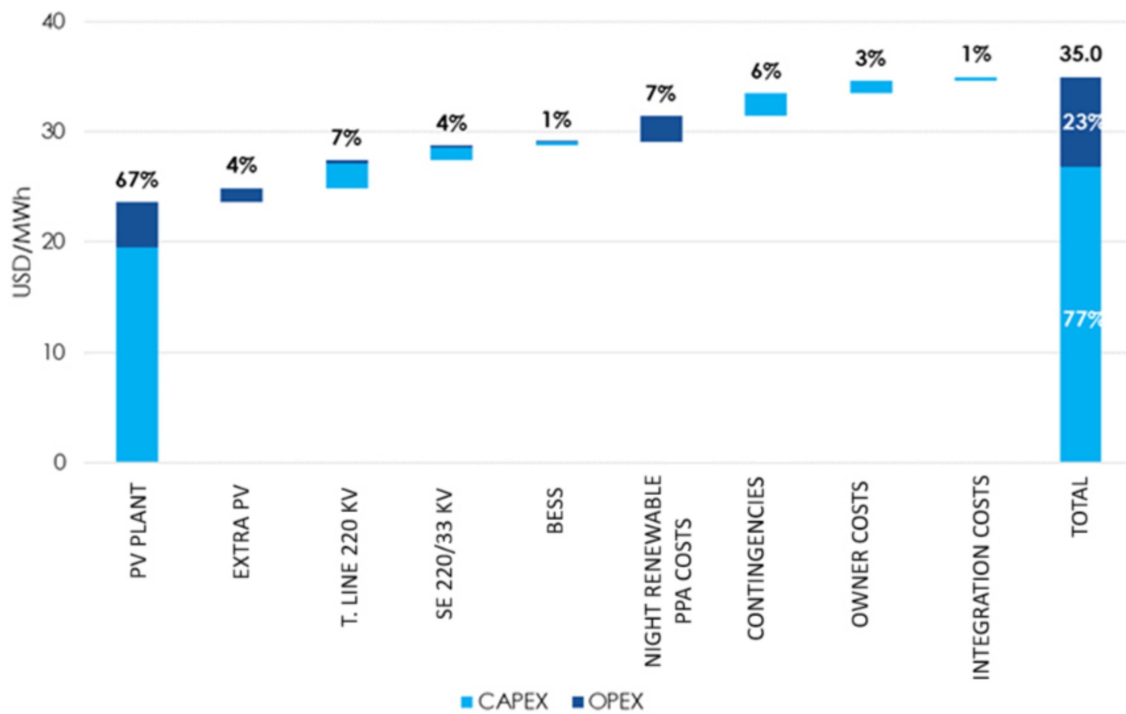

Table 1: Levelized cost of electricity for the first phase of the project.

Source: (Hinicio, 2023).

- **LCOH**

As explained earlier, 93% of the electricity produced is used for hydrogen production in the electrolysis plant. The levelized cost of hydrogen (LCOH) is presented in Table 2:

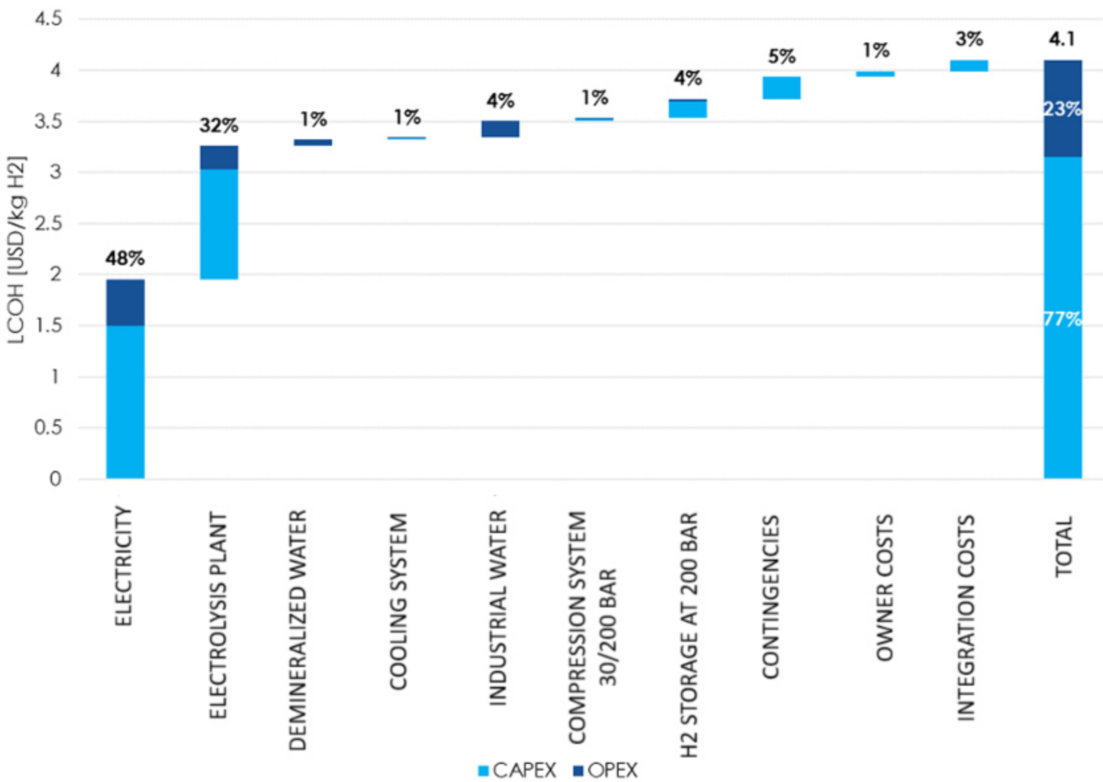

Table 2: Levelized Cost of Hydrogen (LCOH) for the first phase of the project.

Source:(Hinicio, 2023).

The levelized cost of hydrogen for the first phase of the project is 4.1 USD/kg H2, where electricity supply represents 48% of the LCOH. Another system that has a significant contribution to the LCOH is the electrolysis plant, representing 32% of the LCOH. The storage system represents about 4% of the LCOH, while systems such as the cooling system and compressor each contribute only 1% of the LCOH. 77% of the LCOE corresponds to CAPEX, while the remaining 23% corresponds to OPEX. Contingencies, owner costs, and integration costs represent 9% of the LCOH.

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The International Hydrogen Ramp-up Programme (H2Uppp) of the German Federal Ministry for EconomicAffairs and Climate Action (BMWK) promotes projects and market development for green hydrogen in selected developing and emerging countries as part of the National Hydrogen Strategy.