Whitepaper

What would make an international Power-to-X project successful?

Results of the Chilean-German Summer School on Power-to-X in Punta Arenas, Chile, January 12-17, 2025

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1. Introduction and Motivation

Power-to-X (PtX) technologies are expected to play a pivotal role in the global energy transition. These technologies convert renewable electricity into sustainable fuels and chemicals. However, successfully deploying these technologies requires technical progress, systemic integration, policy support, and international cooperation.

The Chilean-German Summer School on PtX in Punta Arenas addressed these needs by convening early-career researchers, industry representatives, and institutions from Chile and Germany. Together, they explored the technical, economic, environmental, and societal challenges and opportunities of PtX implementation.

This whitepaper summarizes the summer school's key insights, discussions, and outcomes, providing participants with a structured reference to revisit after the event. Particular emphasis is placed on collaborative group work, especially the final Work Café session, to ensure that core ideas and conclusions remain accessible for further reflection.

Beyond documentation, the whitepaper lays the groundwork for future academic or industry-oriented publications. By highlighting research gaps and outlining opportunities for cross-project collaboration, the paper aims to foster continued dialogue and innovation in the PtX field.

1.1. The Power-to-X Summer School 2025 in Punta Arenas

The Summer School, launched under the German-Chilean energy transition partnership, was designed to bridge the gap between ambitious policy targets and the practical realities of PtX deployment. By combining technical, economic, environmental, and social perspectives, the school provided early-career researchers and professionals from both countries with focused training and a platform for knowledge exchange between the two countries. Holding the event in Punta Arenas, the regional capital of Magallanes and an emerging PtX hub, emphasized its strategic relevance.

The program was co-hosted by the Karlsruhe Institute of Technology (KIT), the Universidad de Magallanes (UMAG), the Solar Energy Research Center (SERC) Chile, the Institute of Complex Systems Engineering (ISCI), and the Universidad de Chile. Funding came primarily from Germany's Federal Ministry of Education and Research (BMBF), Chile's development agency CORFO, the National Agency for Research and Development (ANID) FONDAP, and the Kopernikus Project P2X of BMBF, with additional support from industry partners ABB and Gasco. Throughout the week, exhibitors such as Y-Tec, Ferrostaal, Ventus, NEOZET, and Neuman & Esser showcased real-world PtX applications.

Thirty-two delegates, including Ph.D. candidates, postdoctoral researchers, junior faculty, and other professionals, represented disciplines ranging from engineering and the natural sciences to economics and policy. This combination of Chilean and German perspectives fostered genuinely interdisciplinary networks.

1.2. Program highlights:

- Core curriculum: Lectures on PtX fundamentals, system integration, and Chile-specific deployment conditions established a shared technical foundation.

- Industry insight: ABB, Gasco and Neuman & Esser presented commercial projects, while start-up's Reborn Electric Motors, INERATEC, Spark eFuels and Phlair highlighted emerging technologies and business models.

- Networking and exchange: Five-minute pitches from participants, two industry-sponsored dinners and an additional official dinner encouraged informal dialogue with senior experts. Cultural activities, such as a guided city tour and an excursion to a historic fort, further strengthened personal connections.

- Site visit: A field trip to HIF Global's Haru Oni plant, one of the world's first large-scale PtX demonstration projects, anchored classroom learning in real-world practice.

2. Context: Germany-Chile Cooperation in the Energy Transition

Germany and Chile have established a strong bilateral relationship in the field of renewable energy and the energy transition, marked by numerous cooperation agreements, joint research initiatives, and political dialogue. These efforts reflect both countries' commitment to achieving climate goals and defossilizing their economies through innovation and international collaboration.

The international context adds urgency and relevance to these efforts. The impacts of climate change, heightened by extreme weather events and shifting global climate patterns, underscore the need for rapid defossilization. At the same time, geopolitical developments, particularly the Russia-Ukraine war, have reshaped the global energy landscape and highlighted the vulnerability of fossil fuel supply chains and the need for resilient and independent energy systems. In this environment, PtX technologies are gaining traction as a key pillar of future energy systems and global energy security.

Chile is uniquely positioned in this transition due to its abundant renewable energy resources, especially the strong and steady wind in the Magallanes region in southern Patagonia and the enormous photovoltaic potential in the northern Atacama Desert. This resource base, combined with stable political conditions, gives the country a strategic advantage in the emerging global PtX economy.

Over the past two decades, Chilean governments have consistently advanced energy policies to promote renewables and green hydrogen, irrespective of each government's political orientation. Key milestones include the publication of Chile's National Green Hydrogen Strategy in year 2020 and the Nationale Green Hydrogen Action Plan 2023–2030, which aim to position Chile as a leading exporter of clean hydrogen and its derivatives. This strategic ambition is backed by a dynamic financial and investment landscape. The Chilean government has launched various incentive schemes to support hydrogen innovation and infrastructure development, while international partnerships, including with Germany, have provided additional momentum. Joint funding mechanisms and cooperation platforms have become central instruments in fostering the PtX value chain between both countries.

In recent years, several initiatives have promoted networking and knowledge exchange between German and Chilean stakeholders. These include scientific workshops, business delegations, bilateral energy partnerships, and summer schools such as this one, which serve as platforms for co-creation and joint learning. At the regional level, the Magallanes region has seen the announcement of several large-scale PtX projects, most prominently the Haru Oni project by HIF Global, which began construction in 2021 and started commissioning at the end of 2022 [1]. These projects are expected to play a central role in Chile’s hydrogen economy by demonstrating the feasibility of export-oriented PtX production based on wind energy.

Despite this momentum, a gap remains between national targets and the current state of progress. Infrastructure bottlenecks, regulatory uncertainties, and market immaturity continue to pose challenges for rapid deployment. Accelerating PtX development will require integrated efforts across government, industry, and civil society. Nevertheless, the opportunities for the Magallanes region are considerable. According to several studies, the capacity factor of onshore wind parks in the Magallanes is about 55-65% due to strong winds [2]. PtX can drive regional development, create high-quality jobs, foster industrial integration, and strengthen Chile’s position in the global clean energy transition. Expectations are that Magallanes will serve not only as a production hub but also as a model region for sustainable development in the PtX era.

For Chilean projects, the scenario projects a yearly production of between 65.14 and 567 kt of hydrogen (H_2) in the Magallanes Region for 2040, according to different scenarios presented in the Chilean Long-Term Energy Planning (PELP) [3].

Regarding LCOH, initial studies estimated it at around 1–1.5 USD/kg in Chile by the year 2030 [4]. However, these values do not include storage or transportation costs, which represent a decisive factor; therefore, realistic values are closer to 3 USD/kg [5].

As part of its national energy transition strategy, Germany anticipates rapidly growing demand for hydrogen and its derivatives. The total requirement is expected to be between 95 and 130 TWh by 2030, with an estimated 45 to 90 TWh likely to be supplied from international partners. This reliance on imports is expected to intensify in the coming decades. Long-term projections indicate a substantial increase in demand, with estimates reaching up to 500 TWh for hydrogen itself and additional 200 TWh for derivative products by 2045. These figures underscore the strategic importance of establishing robust international supply chains and partnerships for hydrogen imports.

2.1. Group Work I: Identifying Key Topics for a Successful International PtX Project

Group work formed a central element of the Summer School’s structure, aiming to foster interdisciplinary collaboration and problem-oriented thinking. Participants were divided into groups based on their academic and professional backgrounds to ensure a balanced mix of technological, social, and environmental expertise.

The first group session focused on identifying key factors necessary for the success of international Power-to-X projects. In facilitated discussions, each group explored a range of challenges and success conditions from different disciplinary angles. The category 'process intelligence' includes technological aspects such as digital twins, predictive control strategies, remote operation, and maintenance. In contrast, the category 'PtX development identity' addresses the socio-regional dimension, emphasizing how local communities strongly identify with the technology, fostering a sense of pride in their region as a pioneer of green molecules and thereby supporting its development.

Following the initial brainstorming phase, a Mentimeter poll was conducted to collectively prioritize the topics (Figure 1).

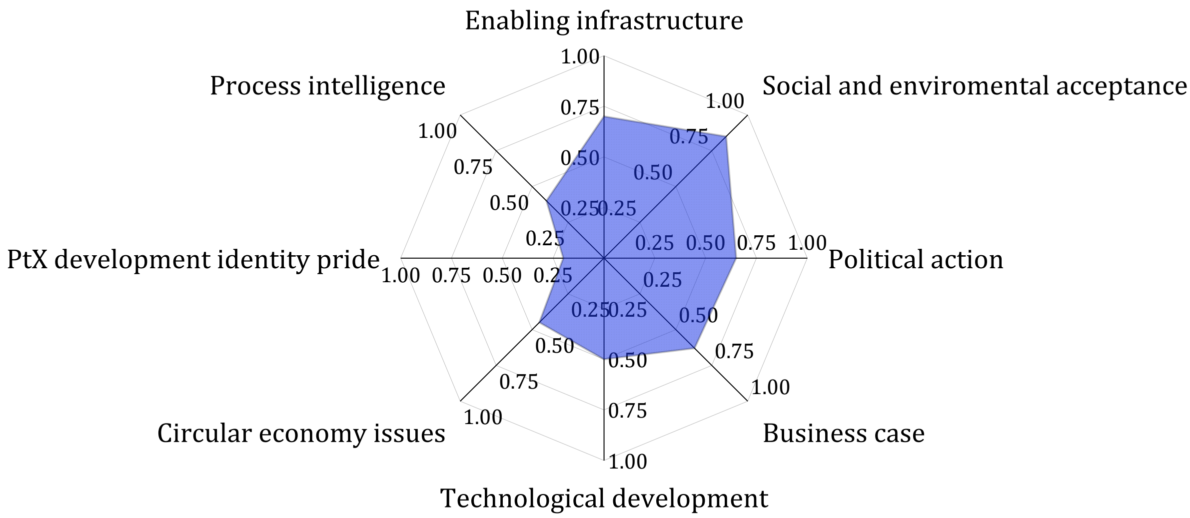

Figure 1. Identified key topics to develop successful international Power-to-X projects. Power-to-X Summer School, Punta Arenas, 2025.

The four most critical themes identified for further discussion were:

- Public Acceptance
- Logistics and Infrastructure
- Financing Strategies of Projects
- Technological Improvements

These topics served as the foundation for the deeper, structured group discussions that followed in the next stage of the program. For the sake of completeness, the overarching topic of "Regulatory issues" was also included in the evaluation.

2.2. Group Work II: World Café Discussion Format

The second group session was organized in the form of a World Café, allowing participants to engage in rotating, in-depth discussions on each of the four selected key topics from the Group Work I. Each topic was discussed for 45 minutes in a small group setting, encouraging active participation and the exchange of diverse perspectives.

At the end of the session, the results were synthesized and presented by designated topic representatives in concise 10-minute summary presentations during the final plenary session. This provided all participants with a comprehensive overview of the discussions and insights developed across all groups.

The outcomes of the World Café discussions form the basis for the subsequent sections of this whitepaper, where they are further analyzed and placed in a broader context.

3. Key Findings in the Topic Areas

Building on the group activities and discussions outlined in previous sections, particularly the selection of key topics and the outcomes of the World Café format, the following section summarizes the main findings in each thematic area. Regional and National Perspectives in Chile; Social and Environmental Acceptance; Infrastructure; Financing of PtX Projects; Regulation; and Technical Improvements.

3.1. Social and Environmental Acceptance

3.1.1. Win-win scenarios and tangible benefits for local communities

To promote the development of industrial projects, new projects must be accepted by the local community and improve the quality of life for its residents. Therefore, design and work plans should focus on balancing the project's impact with tangible benefits for citizens to ensure a sustainable and harmonious relationship with the environment.

Currently, the region's road networks are limited. Additionally, some of the population must travel by sea to reach areas such as Porvenir. According to projections of installed electrolysis capacity, the population and infrastructure needs, including roads and ports, would increase. Thus, new PtX projects could contribute positively to the community by co-financing public infrastructure, generating direct benefits for the population. In addition, the implementation of innovative processes would promote the training of specialists in PtX technologies and help retain local talent that might otherwise seek employment elsewhere.

Financial incentives, scholarships, and other forms of full or partial support for vocational training within the community could also strengthen local public opinion.

Regarding economic development, there was a consensus that companies should pay taxes in the region to directly contribute to the strengthening of the local economy. The local population recognizes this as one of the main decision-making factors in economic terms, along with the development of public infrastructure. Companies should also promote employment in the community by hiring locally. However, no studies have been found that project the number of floating populations or the required infrastructure. H_2 Chile [6] developed some general information about the human capital required for these industries in Chile. The promotion of value chains with regional suppliers is also desirable. These initiatives could foster innovation and economic growth in sectors not traditionally associated with the hydrogen industry, yet adaptable to offer solutions for various stages, including installation, operation, and maintenance. Establishing early agreements could have a positive impact on project approval and foster the creation of indirect employment.

3.1.2. Environmental Impacts

The environmental impact assessment, which considers effects on the landscape, wildlife, and biodiversity, was also deemed highly relevant. First, reforestation and ecosystem conservation were discussed. Generally, the hydrogen projects in Magallanes do not involve felling native trees or using protected areas, such as national parks. Access to the Environmental Impact Assessment reports for each project to corroborate this information can be found at [7]. Wind turbine installations account for the largest land use, as they require minimum spacing to ensure optimal energy output. This requires the use of land for foundation installation and may impact groundwater and the ecosystem. It is currently unknown whether evidence of this impact exists in pristine regions and extreme climates. Furthermore, sheep farming and other livestock activities occupy a significant portion of Magallanes' land. The emergence of the energy sector could mean changes in other economic activities. Although previous studies have been found regarding the potential impact of installing wind turbines and transmission lines [8], reports for Magallanes are scarce. Some of them suggest to make efforts to avoid negative impacts [9]. Based on the above, we should study the detected impacts and propose appropriate mitigation measures or financial compensation.

Water demand, waste management, and pollution reduction were discussed. Thus far, the green hydrogen and derivatives industry appears to be completely clean and free of harmful or polluting emissions. The emphasis is on the reduction of CO_2 emissions offered by green hydrogen compared to steam methane reforming (SMR), as well as the energy efficiency and economic benefits which this new industry could bring to project developers. However, it is essential to review lesser-known details of the industry. For instance, there is no clarity regarding the water demand and how it competes with human consumption, irrigation, and so on. Although Chile has a long coastline, recent studies have indicated that only a few locations are currently suitable for desalination [10]. This could be taken into account for Magallanes. The environmental impact of brines generated during seawater desalination remains unresolved. It is known that for every MW of installed electrolysis power, approximately 450 kg of H2 is produced per day (depending on the technology used), which, in turn, requires approximately 5,000 kg of pure (deionized) water per hour, based on [11]. This implies an even greater volume of brine that must be returned to the sea as a byproduct of the purification process.

In this regard, fishermen argue that desalination plants could seriously compromise local marine ecosystems, affecting fishing and the economy [12][13]. Soil and landscape alteration could also have an impact, as has occurred in other countries [14][15]. Additional water may be required for cooling processes, and residuals may sometimes be generated. Before building new plants, the community needs to understand the potential effects, as well as the solutions or protocols provided by companies.

3.1.3. Renewable energy and energy efficiency educational programs

Today, Punta Arenas is the most populous area in the Magallanes Region. Due to its location at the southernmost tip of the American continent, it experiences very low temperatures in the winter, creating a high demand for natural gas as the primary energy source. Furthermore, the Magallanes electricity system (SEM) operates independently from the rest of the country and primarily produces electricity from oil and natural gas. Consequently, the region also contributes to the country's CO_2 emissions, despite its particularly favorable conditions for wind energy. In this context, energy efficiency plans must be strengthened in homes, industries, and public institutions. Community education programs on energy conservation and efficient energy use should also be implemented. These initiatives will facilitate the region's transition to renewable energy.

Finally, we believe that approving and implementing initial small-scale projects will provide the population, researchers, and investors with relevant information, allowing for a change in mindset regarding real-life applications instead of relying solely on theoretical information. In this context, new training and teaching programs on climate change and resilience are recognized as important, as they will enable the community to understand the associated risks of delayed decisions and unfounded conclusions about the impact of new technologies. To this end, it is important to carry out training and dissemination plans with and for the community.

3.2. Logistics and Infrastructure

The successful implementation of PtX projects depends on efficiently transporting and installing large-scale equipment and reliably supplying essential feedstocks, such as water, CO_2, and other chemicals. Logistics and infrastructure are crucial to determining project feasibility, especially when deploying plants in remote or underdeveloped regions. In addition to transporting electrolyzer units and supporting infrastructure, PtX projects must ensure the efficient movement of large volumes of produced fuels, as well as implement proper waste management, personnel accommodation, and training at operational sites. Careful planning is required to minimize costs, avoid delays, and ensure environmental sustainability.

One of the primary obstacles is the limited availability of transport routes and infrastructure in remote regions, such as Chile's Magallanes area, where many PtX projects are planned. The lack of well-developed roads, ports, and rail networks during construction complicates the movement of large equipment and raw materials. The sheer size and weight of PtX components, such as industrial-scale electrolyzers and CO_2 capture units, increase logistical complexity as well. Moreover, transporting the structural components of wind power plants, particularly towers and blades, involves higher logistical complexity. Long transport times and multiple transshipment points increase the risk of delays and cost overruns, so early infrastructure assessment and planning are essential.

During production, PtX products must be transported to consumers, who are usually not located near the remote plant. Depending on the scale of the operation, transport via road, rail, pipeline, or ship is required to supply consumers in local, national, or international locations. Regardless of the chosen mode of transport, energy efficiency and carbon footprint must be considered due to their significant influence on the overall price and ecological viability.

Addressing these challenges requires a combination of infrastructure assessment and optimization. Feasibility studies can determine the most efficient transport routes, and existing infrastructure can be upgraded, both of which can significantly reduce logistical hurdles. Retrofitting existing infrastructure, for instance, modifying port facilities to handle oversized cargo, offers a cost-effective alternative to building entirely new transport networks. Another viable solution is using modular plant designs where smaller transportable units are assembled on site rather than shipping large monolithic structures.

To mitigate these risks, sustainable construction practices should be prioritized. Techniques such as closed-loop resource management, including water recycling and waste heat recovery, can minimize the environmental footprint of PtX infrastructure. Additionally, engaging with local communities, environmental groups, and policymakers early on is crucial for addressing concerns and ensuring long-term project acceptance. Since many legal hurdles arise when local acceptance is low, local communities should benefit financially from projects in their region. For example, they could receive reduced energy prices or taxes could be paid locally.

Despite the very high wind energy potential in the Magallanes region, specific regional characteristics need to be discussed and considered. Magallanes is predominantly rural, and as shown in Table 1, the local towns are relatively small, with the capital Punta Arenas accounting for approximately 166,533 inhabitants [16]. The infrastructure and electricity networks operate as an isolated system without any interconnection to the rest of the Chilean grid. Power supply is mainly based on natural gas and diesel, while Punta Arenas is partly supplied by wind energy. Since there is no large-scale industry in Magallanes (except for Methanex, which produces methanol with its own energy supply), there has been no significant grid expansion. At the same time, several thousand tourists visit the region every year to explore the Torres del Paine National Park, which underscores the importance of protecting the area for environmental conservation.

Figure 2 and Table 1 show the main characteristics of the energy systems in the Magallanes Region.

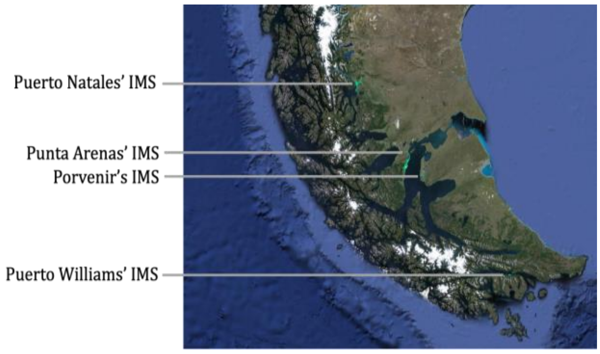

Figure 2 Map of the Magallanes Region with the largest cities and towns [17].

Table 1 Overview of energy supply in cities and towns in the Magallanes Region [17].

Region	System	Installed capacity [MW]	Energy mix (installed capacity)	Quantity of clients	Peak demand in 2023 [MW]
Magallanes	Puerto Natales	13.51	68.6% natural gas 31.4% diesel	10,879	4.27
	Punta Arenas	102.36	81.1% natural gas 6.3% diesel 12.6% wind	56,033	48.21
	Porvenir	11.07	45.0% natural gas 55.0% diesel	2,708	2.56
	Puerto Williams	2.38	100% diesel	777	0.33

Finally, implementation strategies must prioritize regulatory and administrative efficiency. Complex permitting processes often delay PtX projects. Additionally, coordinating stakeholders across multiple regulatory environments can complicate compliance and approvals. Streamlining approval processes and harmonizing regulations between jurisdictions can significantly accelerate project timelines. Collaborating with local governments to integrate PtX infrastructure into existing networks, such as industrial hubs or renewable energy clusters, can enhance project feasibility. Programs that transfer knowledge and build local expertise in PtX infrastructure development are also essential for long-term sustainability.

A multifaceted approach that balances economic feasibility, environmental sustainability, and regulatory efficiency is required to address the logistical and infrastructure challenges of PtX projects. Early-stage infrastructure planning and collaboration across industry sectors are critical to optimizing transport and installation logistics. Furthermore, integrating sustainable design principles and fostering public-private partnerships can enhance project viability. Overcoming these barriers enables more effective development of PtX infrastructure and supports the transition to a global renewable energy economy.

3.3. Financing Strategies of Projects

The results of the key topic, "Business Case" emphasize the importance of robust, flexible, and context-sensitive strategies for ensuring the long-term success of PtX projects. Several interrelated factors contributing to the development of resilient business models and the enhancement of the bankability of such initiatives were identified.

A clear understanding of market demand was emphasized as a prerequisite for defining viable business cases. Before investing in infrastructure, it is crucial to determine the end users, required products, and operating conditions. A demand-driven approach aligns production capacities with actual market requirements, reducing investment risk.

Another recommendation is to diversify product portfolios and value chain components. Offering a variety of PtX products, such as green hydrogen, e-methanol, and e-fuels for different markets, increases resilience and enables multiple revenue streams. Simultaneously, diversifying key inputs, such as CO_2 sources, the water supply, and access to renewable energy, improves operational flexibility and scalability.

Locating early projects in geographic and regulatory "sweet spot" regions was identified as a strategic advantage. Regions with abundant renewable resources, transparent permitting processes, and basic infrastructure offer favorable conditions for the successful implementation and demonstration of projects [17].

Integrating PtX projects into local economic ecosystems can support job creation, strengthen regional expertise, and encourage collaboration with existing industries. These effects reinforce the economic case and contribute to long-term social acceptance. In this context, tourism, particularly in sensitive areas such as Patagonia and Antarctica, was identified as a potential driver of demand for sustainable fuels.

The concept of collaborative value creation was deemed essential. Business models that benefit all stakeholder groups, including communities, investors, and public institutions, across economic, social, and ecological dimensions are more likely to earn trust and accelerate implementation.

Financing PtX projects, especially in the early, capital-intensive stages, remains a significant challenge. Green investment funds, blended finance models, and public-private partnerships can provide customized financial support in the form of equity, loans, or guarantees. Additionally, insurance mechanisms comparable to offtake agreements can stabilize revenue expectations and mitigate market risk. The economic viability of logistics and infrastructure development is another major concern. High initial investment costs combined with fluctuating energy prices and uncertain regulatory frameworks make securing financing for PtX infrastructure challenging. Limited investor confidence can further delay project timelines. One key strategy to address these challenges is to establish public-private partnerships that distribute financial risks and leverage government incentives to support infrastructure development. Standardizing PtX plant components can reduce costs by enabling economies of scale in manufacturing and transportation. Additionally, national governments must establish clear roadmaps for pursuing PtX technologies to provide investors with greater confidence in future demand. In terms of infrastructure, adapting existing facilities for PtX production, storage, and distribution is essential. This includes retrofitting ports, pipelines, and refueling stations, as well as ensuring compatibility with existing logistics systems [18][19].

Carbon pricing instruments, such as carbon taxes and emissions trading systems, were identified as important tools for making PtX products more competitive. These mechanisms internalize environmental costs and encourage investment in carbon-neutral alternatives. Tax relief and guaranteed premium prices were also recommended to incentivize the production and consumption of green fuels.

Generating and trading verified emission reduction certificates was considered a complementary source of income. Certification mechanisms add transparency, improve accountability, and enable participation in global carbon markets.

Finally, early adopters need support. Since pioneering projects often face elevated risks and uncertainties, mechanisms such as innovation funds or pilot support schemes are necessary to share financial burdens and secure early learning effects.

3.4. Regulatory Issues

3.4.1. Necessary regulatory frameworks to facilitate project development

Traditionally, hydrogen has been produced in petrochemical plants and used as a chemical input in industrial processes instead of as an energy source. The rapid advance of interest in renewable hydrogen for energy applications, with large-scale projections, has created challenges that must be addressed to ensure environmental and social compliance and to guarantee the safety of industrial and end-user processes. To this end, new regulatory documents, decrees, and guides have been developed for the implementation of pilot and industrial plants, storage, transportation, and more. In Chile, the plan has been implemented in accordance with the Chilean Green Hydrogen Strategy, published in 2020. Some recent advances in the field are presented below:

Decree No. 13, "Safety Regulations for Hydrogen Installations and Modifications to the Regulations for Gas Installers", was published in 2022 and modified in 2024.

The Chilean Green Hydrogen Action Plan (2023–2030) was launched in 2023. The plan outlines short- and medium-term actions with specific responsible parties that will enable the development of the green hydrogen industry and its derivatives in Chile. In terms of regulations, some actions include launching and implementing the work plan to enable industry regulations and promoting specific regulations to enable the desalination of seawater.

In 2021, the Energy Ministry gained jurisdiction over H_2 with the passage of Law 21.305, modified DFL1 [20]. Some of the regulations that need to be discussed are mentioned below, and some are currently in progress:

- Security aspects associated with liquid hydrogen.
- Set the parameter quality for hydrogen.

- Define aspects associated with the marketing of hydrogen as energy (Decree DS132)
- Add hydrogen to the natural gas pipeline for residential use (H_2 + NG)
- Topics associated with the transportation of hydrogen gas by pipes.
- Incorporate associated aspects into the mixture of natural gas (NG) with hydrogen in interior networks.
- Technical requirements of security in dispensing of H_2 gas to vehicles on public roads and off-road.
- Technical requirements for H_2 filling stations gaseous in conjunction with other fuels.
- Set specifications or quality parameters for mixtures of natural gas and hydrogen.

The Chilean Health Ministry also oversees certain tasks. The main two under-modification processes are:

- Storage of dangerous substances: Review and update the conditions of storage of dangerous substances defined for the different types of facilities.
- Clean and safe place for work. Update the regulations, considering security measures when there is exposure to chemicals.

Additionally, work is being undertaken to modify the Circular B32/04/2020 on guidelines for the issuance of industrial qualifications. Specific guidelines will be generated for the review of hydrogen and ammonia projects, applicable in the Chilean Environmental Assessment Service (SEIA) and in the sectoral processing of permits.

Regarding the Transport and Telecommunications Ministry, the next topics are in progress:

- Transportation of dangerous cargo: Modifying decree D298 will be analyzed through regulations on specificities (pressures, temperatures, etc.).
- It is still necessary to define how to approach the retrofit, so a dialogue process will begin with the private sector to understand their needs and determine actions.

From a territorial planning perspective, Circular DDU 470, issued in 2022, regulates territorial compatibility issues [21]. This document focuses on land use for energy and productive activities, urban planning standards, and building requirements.

The 2024 Guide for Application for Authorization of Special Hydrogen Projects is intended for companies and individuals who wish to implement projects involving technologies beyond the scope of Supreme Decree No. 13 of the Ministry of Energy. Its purpose is to provide a clear guide for obtaining authorization from the Chilean Superintendence of Electricity and Fuels (SEC). This authorization is essential to ensure that facilities adhere to the strictest safety standards and international regulations, including those of ANSI, ASME, and ASTM, among others [22].

Despite the progress previously demonstrated, challenges remain in processing and managing sectoral permits in Chile. The progress of the Chilean Green H_2 Strategy is depicted in Figure 3.

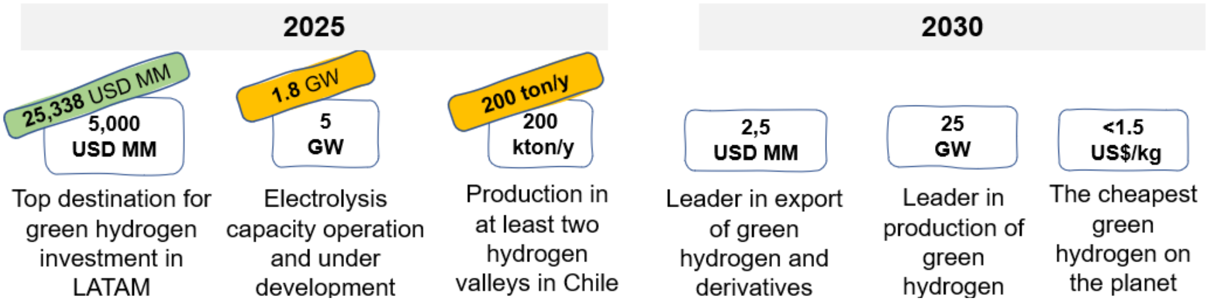

Figure 3 Progress of Chile's Green H2 strategy based on data from Corfo.

To address these challenges, the country introduced the Framework Law on Sectoral Authorizations (Ley LMAS) in 2024, which aims to centralize information, standardize processing procedures, reduce non-regulated requirements, increase transparency, and monitor service performance in real time. In short, the law aims to create a unified system for handling permits and authorizations, which currently operate separately. This will simplify processing and reduce administrative complexity. These advances highlight Chile's interest in becoming a producer and potential exporter of hydrogen and its derivatives. Future actions will focus on strengthening services that provide critical permits for the industry's adequate development and establishing a regionally focused implementation route. The country will also strengthen the Environmental Assessment Service (SEA) and other services involved in the environmental assessment process.

The importance of aligning with international regulations was also discussed. Germany adheres to the EU's regulatory framework for energy and climate, consisting of various legislative texts targeting different sectors. There are six areas of work in this regard: 1) the Renewable Energy Directive (Red II and Red III) [23][24]; 2) the EU hydrogen and defossilized gas market package [24]; 3) Refuel EU Aviation [25] and 4) Refuel EU Maritime [25], which are related to renewable fuels of nonbiological origin (RFNBO) and low-carbon fuels for transportation, such as hydrogen and its derivatives; 5) the Emissions Trading Scheme (ETS) [26]; and 6) the Carbon Border Adjustment Mechanism (CBAM) [27], which are related to carbon pricing mechanisms. This work plan aims to reduce greenhouse gas emissions by 55% for the EU by 2030. The RFNBO guidelines are defined here, and the strategy establishes the regulatory framework for producer-exporter countries whose final market is Europe. Given the urgency of climate change, it is necessary to work in a timely and organized manner with community and private organizations to approve new projects that adhere to international safety standards and achieve concrete, sustainable progress. This should include training plans on regulations to ensure that new projects guarantee the legal requirements of this growing market.

3.4.2. Policies required to attract investors and ensure long-term stability

Investors, governments, and businesses must implement clear, transparent, and investor-friendly policies. These policies should create a stable economic environment, minimize risks, and promote sustainable growth:

- Maintain low inflation and favorable tax policies such as tax incentives and reliefs for long-term investments.
- Transparent Legal System: A fair and efficient judicial system that resolves disputes quickly.
- Regulatory Predictability: Clear, consistent, and enforced regulations to reduce uncertainty.

- Anti-Corruption Measures: Strong governance and anti-bribery laws to ensure a level playing field.
- Public-Private Partnerships (PPPs): Encourage collaboration between government and private sector for infrastructure and innovation projects. Here, the incentive for the creation of hubs could be highlighted. In this way, costs and risks could be distributed among different sectors and not just a few. In Chile, there have been some advances, such as public-private meetings and conversations with specialists and the public, to define some guidelines and a general framework for the discussion of technological and industrial hubs or valleys. For instance, they have defined the ideal size for production and storage, as well as the optimal distance from ports or power lines.
- Access to Finance: Develop financial markets that facilitate loans, venture capital, and stock market access.
- Sustainable Energy Policies: Promote renewable energy and energy efficiency to ensure long-term resilience.
- Sustainable Development Goals (SDGs): Alignment with global sustainability efforts to attract ethical investors.

3.5. Technological Improvements

The large-scale deployment of PtX technologies presents significant technical challenges that must be overcome to ensure their feasibility and competitiveness. These challenges include operating dynamically under fluctuating renewable energy supply conditions, improving process efficiency, and aligning with regulations. Overcoming these obstacles requires advancements in plant design, system integration, and policy frameworks. This section explores the key barriers to technological implementation and outlines potential solutions.

In the context of dynamic operation, PtX systems must adapt to the variability inherent in renewable energy sources. Unlike conventional plants, which operate under steady-state conditions, PtX facilities must be capable of ramping production up or down depending on the availability of solar and wind power. Electrolyzers and synthesis units require enhanced flexibility to efficiently manage these fluctuations. One key strategy is to minimize storage requirements because excessive hydrogen or synthetic fuel storage increases capital expenditures (CAPEX). Decentralized plant structures that are directly integrated with renewable energy hubs can optimize energy utilization and reduce transmission losses. A modular plant design approach enhances adaptability further, enabling a more flexible response to variable energy inputs. Additionally, developing cost-effective CO_2 capture technologies, such as direct air capture (DAC) and improved point-source CO_2 separation, is essential to reducing operational expenses and making PtX processes economically viable [28][29][30][31][32].

Process efficiency and resource integration also present significant challenges. In order to compete with fossil-based alternatives, PtX technologies must achieve high conversion efficiencies. One strategy is to optimize the integration of waste streams and process heat to ensure that excess energy and by-products are recycled effectively. Closed carbon and water cycles further enhance sustainability by reducing resource consumption and environmental impact. Improving electrolyzer efficiency, such as reducing overpotential losses and extending operational lifetimes, contributes to reducing overall energy demand and maintenance costs. Fostering the parallel development of multiple technologies, such as different electrolysis and synthesis methods, prevents reliance on a single technological approach, mitigating risks and enhancing resilience in PtX deployment [29] [33][34].

The commercial viability of PtX technologies is largely determined by regulatory and policy frameworks. Current market structures often favor fossil-based products, creating an uneven playing field. For PtX-derived fuels to be accepted in the market, it is crucial that they meet the same quality standards as their fossil counterparts. Simplifying permitting and certification processes can reduce barriers to project deployment. Targeted incentive mechanisms, such as carbon pricing schemes and green hydrogen subsidies, can improve financial feasibility. Harmonizing international standards will facilitate cross-border trade and investment in PtX infrastructure.

Scaling PtX technologies from pilot projects to full-scale industrial implementation requires improvements in plant engineering, supply chain logistics, and standardization. Early collaboration among companies in the design and engineering phases can streamline project execution and reduce costs. Standardizing key PtX plant components, such as electrolyzers, synthesis reactors, and storage units, accelerates deployment and fosters economies of scale. Digitalization and artificial intelligence further enhance system performance. Digital twins and predictive control enable real-time process optimization and early fault detection. Automated modular plants and IoT-based remote monitoring reduce operational costs and increase scalability, ensuring the long-term viability of PtX solutions [35][36][37].

Addressing these technical challenges is essential for PtX technologies to scale up and integrate seamlessly into the global energy transition. Innovation in system flexibility, efficiency, and regulatory adaptation must be driven by research and industry collaboration. Overcoming these hurdles will allow PtX to establish itself as a cornerstone of a sustainable, renewable energy economy.

4. Research Gaps and Call for Action

The summer school activities and participants' workshops agree on a prosperous future for clean energy development in the Magallanes region. However, there was a consensus that certain issues need to be studied or clarified in greater detail to gain a deeper understanding of the potential implications of PtX technologies. The main gaps and opportunities identified through in-depth dialogue among colleagues are listed below. These gaps present an opportunity for analysis by specialists in different fields, as well as stakeholders from academia, industry, and the public sector.

It is recognized that local public opinion must be considered in investment projects. It is important to consider the knowledge of the population alongside the technological aspect of the projects (a transdisciplinary approach is envisioned). Furthermore, it is desirable for the industry to compensate and retribute to the community. This outcome may not necessarily imply economic benefits, but it could include the development of infrastructure for public use, improvements to health systems, and access to courses and training.

As mentioned, social acceptance requires understanding the impact of this sector on the local economy and job creation. While some studies project the nationwide demand for industrial professionals and technicians, there are no specific studies on the type and number of professionals needed in the Magallanes Region in the coming years.

A Life Cycle Assessment (LCA) of the entire Power to X value chain is necessary, as the impact of secondary processes may not be fully understood, particularly in areas of high environmental value, such as the Magallanes Region. Issues such as land use, location and size of desalination plants, water treatment, and industrial waste need to be addressed in detail to provide the local population with greater confidence.

Additionally, there is a recognized need to adapt green hydrogen and derivative production processes to the energy supply conditions of isolated power systems with variable renewable energy sources.

A sudden increase in the floating population will require more infrastructure and services. This growth must align with the region's and country's sustainable development policies. Dedicated studies are required to accurately project social and economic aspects and develop work plans in line with sustainable development goals.

There is a need to accelerate the development of regulations that define the rules of the game and serve as the regulatory framework for projects. Moreover, Article 6 of the Paris Agreement may provide a foundational framework to promote international cooperation in achieving climate change goals, and it could be strategically leveraged to establish an energy justice-based approach for green hydrogen development in Chile's Magallanes region. This requires strong commitments from local, national governments, and international partners to develop policies that accelerate the PtX industry and ensure a just energy transition. Social stakeholders and lawyers must participate in working groups to ensure balanced projects from which all stakeholders can benefit.

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