Shared Green Hydrogen Infrastructure in Antofagasta and Magallanes

Final Report

Joris van de Klundert, Pablo Garcia Silva, Tito Homem de Mello, Macarena Larrain, Cesar Cerda, Juan Miguieles

Universidad Adolfo Ibañez

November 27, 2025

This report may be freely distributed for non-commercial purposes. The online appendix is available at https://www.researchgate.net/profile/Joris-Van-De-Klundert-3.

No part of this report or the appendices may be reproduced without written permission by the first author.

Contents

Preamble 3
Executive Summary 4
Introduction 5
Research Design & Methods 8
Mixed Methods: Qualitative Research 8
Mixed Methods: Quantitative Research 9
Cooperative Game Theory for Cost Allocation 10
Absolute Environmental Sustainability Assessment (AESA) for social and environmental impact 11
Results: Qualitative Findings 14
Global Developments 14
Views on National Developments 14
What GH2 Value Chain Infrastructure can be shared? 15
Results: Quantitative Findings 18
The Economics of Sharing Infrastructure among GNH3 Export Value Chains 18
Case Study Magallanes 21
Scenarios 21
Cost Allocation 23
Absolute Environmental Sustainability Assessment 24
Case Study Antofagasta 28
Existing projects and GNH3 Export 28
Absolute Environmental Sustainability Assessment 29
Domestic Off Take 31
Impact analysis for Domestic Off Take Scenarios 35
Discussion and Conclusions 36
References 39

Preamble

Green hydrogen is planned to play an essential role in the global energy transformation towards clean renewable energy. Due to its proximity to the Pacific Ocean and its access to abundant solar and wind energy, Chile has significant natural comparative advantages and opportunities to produce green hydrogen and derivatives. Investment in green hydrogen and derivatives production projects currently in formal stages of approval are already approaching 40 billion euros. The regions of Antofagasta and Magallanes each host almost half of these projects and of expected future projects. Their economies, societies, and environment will be significantly impacted. Thus, it is imperative that such developments consider a regional perspective.

This document reports the findings of a scientific research project that approaches green hydrogen infrastructure from a regional perspective and seeks to identify how sharing of infrastructure among projects can improve the economic, societal, and environmental impact. The research project has been initiated by the embassy of the Kingdom of The Netherlands in Chile and designed in collaboration with Universidad Adolfo Ibañez. The research team of Universidad Adolfo Ibañez conducted qualitative and quantitative scientific research aided by the Dutch companies involved in the PIB ¨ The Green Energy Corridor Chile - The Netherlands¨ and Chilean stakeholders such as Corfo Magallanes and H2 Antofagasta. The research has been partially funded by the Dutch Enterprise Agency (RVO).

Executive Summary

First projects to produce green hydrogen and derivatives has been approved in the Chilean regions Antofagasta – Atacama and Magallanes. Moreover, the combined value of the portfolio of announced green hydrogen production in these regions exceeds 37 billion Euros. Chile´s green hydrogen industry is taking off and may substantially contribute to decarbonizing operations across the globe and preventing negative impacts of transgressing the boundaries of a safe and just operating space for humankind and planet Earth.

Together, the projects would also have significant economic, social, and environmental impact on Chile´s Antofagasta-Atacama and Magallanes regions where the far majority of these projects are located. Even if each individual project is environmentally sustainable, their combined impact may cause transgressions of the regional boundaries of a safe and just operating space. A regional view, and a collaborative approach which captures opportunities to share infrastructure can help guide the development of Chile´s green hydrogen sector to promote both local and global sustainability.

Infrastructure sharing adds complexity to the already substantial challenges faced by the projects and the alternative to ¨go it alone¨ appears to remain attractive. Sharing of infrastructure among projects developed by private partners brings along risks associated with asynchronous advancement, with environmental and financial approvals of projects involved, and with future behaviors. It requires trust and solutions that mitigate risks. Public entities can play an important role in reducing risks and building trust in the regional and national commitment to advancing the green hydrogen industry. Governments at various levels and public entities can promote collaborative development through regulation, financial arrangements, and by taking a proactive and coordinating role.

The business cases of the projects in the Magallanes regions are mostly built around exportation of low-cost green ammonia. The production value chains already maximize economies of scale and leave little room for benefit of production infrastructure sharing. The required logistic infrastructure, however, and especially the port infrastructure that is essential for export, offers important opportunities to improve costs and business cases from a regional perspective. Moreover, sharing of logistic infrastructure appears required to keep regional social and environmental impacts within the planetary boundaries.

The Antofagasta-Atacama region offers the additional perspective of developing green hydrogen value chains for domestic off take and to decarbonize the Chilean economy. These opportunities mostly relate to the mining industry and two of the projects being developed advance in this direction already. Future opportunities that decarbonize primary operations in the mines and the foundries as well as the maritime copper exportation logistics require low-cost green hydrogen production and economies of scale. This necessitates the private and public parties involved to move beyond the sharing of logistic infrastructure and to share production infrastructure across use cases and locations.

Introduction

As of November 2025, the portfolio of announced projects to produce green hydrogen (GH2) and derivatives in Chile contemplates of the installation of 36.3 GW of solar and wind based renewable electricity generation capacity, with 48% distributed in the Antofagasta Region, 42% in the Magallanes and Chilean Antarctic Region [1]. By acquiring and desalinating sea water, these projects are planned to produce 6.3 million tons of GH2 annually as they materialize over the next decade [1]. The combined capacity of these projects is comparable to the total installed capacity of the National Electricity System (SEN) of 38.3 GW [2]. Moreover, their capacity is double the combined wind and solar capacity currently installed in Chile, which stands at 18 GW [1,2]. The first set of projects that have already received or applied for approval has a combined value of more than 37 billion Euros [3].

The renewable energy production only forms the first step of the value chains developed in the GH2 projects, which subsequently involve the production and logistic infrastructure for GH2 and derivatives like Green Ammonia (GNH3) and eFuels, at scales that are unprecedented for Chile and the world. The vast majority of these projects are developed by foreign investors and focus on the export of hydrogen derivatives to meet demand from overseas, such as in Asia and Europe. Figure 1 depicts the value chain for the exportation of GNH3.

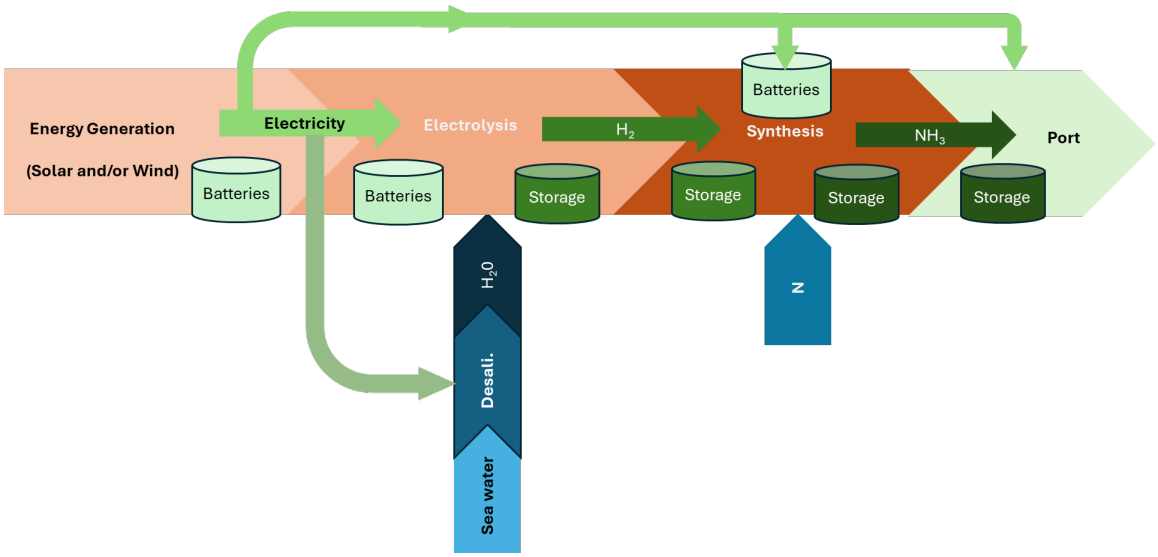


Figure 1: The NGH3 Exportation Value Chain

Domestic off take of GH2 and derivatives in Chile is especially relevant for the decarbonization of industrial and logistics operations in and around the Antofagasta region,

which forms an important location for the mining industry that is responsible for more than half of the value of Chilean exports [4].

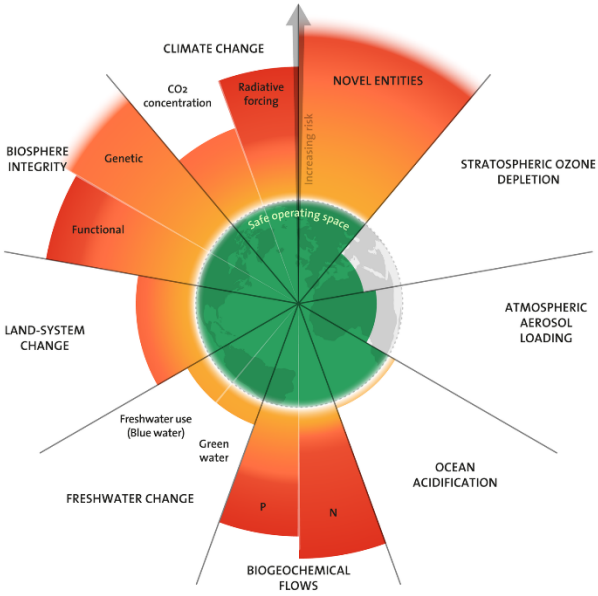


Figure 2: The 2025 update to the Planetary boundaries [8].

The combined projects can make a significant contribution to the global energy transformation and bring enormous economic benefits for Chile. In addition to this economic impact, the operation of these values chains may have important social and environmental impact in Antofagasta and Magallanes, which need not be exclusively positive. As the portfolio of GH2 projects grows and their contribution to global decarbonization efforts becomes more substantial, their local social and environmental impact might increasingly transgress local sustainability boundaries [5,6]. Figure 2 presents the planetary boundaries framework to be considered for this purpose, as well as the present sustainability of global operations.

These developments are well recognized in Chile's National Green Hydrogen Strategy which states *¨sustainable development of this new industry will take into consideration development throughout the country. The interests, activities, groups, collective visions, needs, and strengths present in each region shall be considered when developing projects¨*, thus ensuring that *¨green hydrogen industrial development shall be coherent with its socioenvironmental context…¨* and that *¨this industry shall be developed in harmony with its environment….¨* [4].

This report adopts this regional view and studies regional GH2 value networks rather than the GH2 value chains of individual projects. It studies how such a value network view, which considers a portfolio of projects and opportunities for shared infrastructure, can improve regional economic, societal, and environmental impact.

The research conducted to this purpose takes an inclusive approach, engaging a variety of local, national, and international stakeholders, public and private, explores advantages and disadvantages of sharing infrastructure, and includes qualitative and quantitative analysis. The research goes beyond describing the current situation, as it also presents solutions for current challenges and expansions in pursuit of opportunities to improve global and local sustainability of operations. It develops and presents recommendations to act within the current window of opportunity to contribute to global and local sustainability.

Research Design & Methods

Readers who are not interested in the research methods may prefer to advance directly to the results sections.

Mixed Methods: Qualitative Research

The work conducted to address the research questions followed a mixed methods design. The basis was formed by qualitative research which included a review of grey and scientific literature into the state-of-the-art understanding of shared infrastructure. The review identified 25 scientific publications on GH2 value chains and another 25 on infrastructure sharing in energy networks. The grey literature included relevant documents produced by regional and national governments, as well as by international stakeholders such as the World Bank, Inter American Development Bank, International Energy Agency, the European Union, et cetera. The online appendix enlists all literature included in the review.

The literature review focused on identifying factors that promoted sharing of infrastructure (enablers) and factors that hindered sharing of infrastructure (barriers), as relevant for GH2 value networks. Further, the review identified the results of sharing infrastructure, distinguishing between advantages and disadvantages of sharing. The factors and the results were grouped using thematic analysis [7]. The resulting themes and subthemes formed the guidelines for further qualitative research in the form of individual interviews. The online appendix provides the interview guide.

All interviews were conducted online. The respondents received information about the interview protocol prior to the interview and of the data management protocol. Interviews were recorded after obtaining explicit consent from all participants. The interviews were conducted in English, Spanish, or Portuguese, depending on the preference of the respondent. The interviews were transcribed and anonymized. The interviews in Portuguese were translated to Spanish by a native speaker. Data analysis was conducted in Atlas.ti version 25, initially following a deductive approach [7].

A total of 24 Interview respondents were selected, six from each of four categories:

1. Stakeholders from the Antofagasta region, with an emphasis on H2V projects in more advanced stages of development, e.g. having submitted their environmental impact assessment.
2. Stakeholders from the Magallanes region, with an emphasis on H2V projects in more advanced stages of development, e.g. having submitted their environmental impact assessment.
3. Chilean stakeholders as relevant from a national perspective,

4. International respondents, representing H2V development projects in Australia, Brazil, and The Netherlands (without requiring any relation to Chile),

The respondents from the first three categories provided data that represented various views regarding shared GH2 infrastructure by Chilean stakeholders. The international stakeholders from the 4th category are included for comparative purposes. They help to understand which findings are common to contexts across the globe and which ones are specific for Chile, Antofagasta, or Magallanes.

Mixed Methods: Quantitative Research

The qualitative data from the Antofagasta and Magallanes stakeholders also served as a basis for two quantitative case studies, one for each of these regions. Each of these case studies analyses several scenarios for infrastructure sharing. The Magallanes case study is elaborated first as it focuses almost exclusively on export value chains, shipping GH2 derivatives overseas. It is elaborated using publicly available information [8-11] and in collaboration with Corfo Magallanes and an additional interview with Ultranav. The Antofagasta case study additionally includes value chains towards domestic off take, contributing to achievement of Chile´s national climate goals. It is elaborated with publicly available data [9-12] and based on expert input from H2Antofagasta and Arcadis.

Figure 3: The Magallanes and Antofagasta regions as the origins of global GH2 value chains

Cooperative Game Theory for Cost Allocation

Decisions to share GH2 infrastructure involve many stakeholders and evaluation metrics. This study quantifies effects of infrastructure sharing using economic, societal, and environmental performance metrics [13-15]. When infrastructure is shared, relevant quantities of the shared infrastructure, e.g. the cost or the carbon footprint must be allocated to the value chains of projects to facilitate decisions makers to weigh the pros and cons of sharing infrastructure with other projects. We adopted a cooperative game theory approach and, more specifically, based the allocation on Shapley values [16]. Broadly speaking, Shapley values determine the contribution of each participant by considering how much the overall outcome changes when they join each possible combination of other participants, and then averaging those changes. Shapley values ensure that allocation is fair and that sharing is beneficial whenever benefits are attainable.

A small illustrative example is depicted in Figure 4. On the top panel, there are three projects, each with a separate value chain and hence with a separate port. The costs for projects C,D and E are 402 M€, 405 M€, and 410 M€, respectively (for the purposes of this illustrative example, we assume that all ports cost the same, so the differences result from the pipelines and their costs).

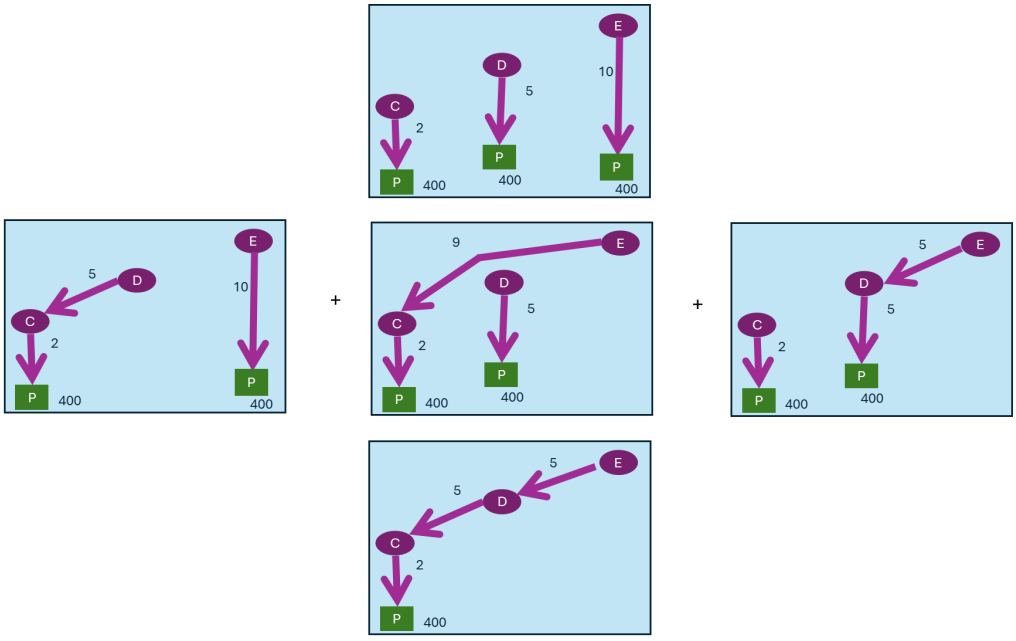


Figure 4 Shapley value calculation example.

The second row presents three more economic ways in which two projects can share ports. For example, on the left-most panel, projects C and D share a port. Since total pipeline costs are not altered, the cost sharing regards only the port and the corresponding Shapley values are 202 M€ and 205 M€. Project E remains at a cost of 410 M€ in this case. The second panel in row two is less trivial. For project C, the Shapley value is the average between (i) the cost of project C built alone (402 M€), and (ii) the additional cost resulting from aggregating project E to project C, compared to the cost of project E alone (i.e., 411-410 = 1 M€). Thus, the Shapley value of project C is (402 +1)/2 = 201.5 M€. Likewise, the Shapley value for project E becomes (410+9)/2=209.5 M€. The same calculations can be made for projects D and E in panel 3 row two. It results in cost of 202.5 M€ for project D and 207.5 M€ for E.

For the third row, the Shapley values are taken as the average over the three sets of Shapley values as calculated by either of the three projects joining the other two. It can be verified that this results in Shapley values of 134.2 M€, 136.5 M€, and 141.3 M€ respectively, for projects C, D, and E.

These methods from cooperative game theory were used to allocate cost and hence to address economic metrics of infrastructure sharing for projects involved (the business case of sharing GH2 infrastructure) [17,18]. They also form the basis for the absolute environmental sustainability assessment.

Absolute Environmental Sustainability Assessment (AESA) for social and environmental impact

After the economic assessment, an Absolute Environmental Sustainability Assessment (AESA) was performed to analyze the environmental implications of sharing infrastructure.

An AESA is an evaluative framework that determines whether a specific activity remains environmentally sustainable in absolute terms, that is, capable of meeting human needs within the Earth's environmental limits (guidance for applying absolute environmental sustainability assessment on activities at different scales). It does so by comparing the environmental burdens of an activity to its allocated share of the environmental thresholds.

The methodological choice to adopt AESA supports the regional perspective of the research aims and questions. It contrasts with a project-based evaluation, which runs the risk of ignoring the combined impact of a portfolio of projects withing a region. Each wind turbine park, electrolysis plant, port, and even each GH2 value chain may by itself meet the criteria for successful EIA application with reference to the current regional base lines. But perhaps projects with a combined number of 3000 wind turbines for all projects in Magallanes, or 5 new ports for exportation in the Mejillones area cannot be developed within regional and planetary boundaries, or only when adjusted to share infrastructure.

This framework allows us to quantify the impact of several projects and to analyze whether their joint implementation raises environmental impacts to unsustainable levels. Conversely, relying solely on comparative frameworks such as life cycle assessment does not necessarily ensure that their operation remains environmentally sustainable in absolute terms [33]. In other words, a relative approach to environmental sustainability assessment does not guarantee that societies remain capable of meeting human needs within the Earth's ecological limits.

An AESA relates the impact of a system to its maximum allowable impact, established by assigning a share of the planet's environmental limit or threshold as quantified, for instance, in the planetary boundaries framework depicted in Figure 2 [5,6,34]. If the environmental impact does not exceed that allocated share, the activity is deemed sustainable. The main steps in an AESA are: (1) estimation of the environmental burden, (2) allocation of carrying capacities, and (3) interpretation of the results.

To determine the environmental impacts, we performed a life cycle assessment for the construction of the port, pipelines, jetties and ammonia tanks required for each case study in Magallanes. The impacts produced due to the movements of ships and truck are not accounted for, because it is assumed to be equal in both case studies. In addition, we calculated the impact of the operation of the electrolyzer and energy generation for the cases of Antofagasta.

The Life Cycle Inventory for the construction of the port and pipes was taken from the Environmental Impact Assessment of HNH Energy presented to Chile's Environmental Assessment Service (Servicio de Evaluación Ambiental, SEA). Furthermore, based on cost it was assumed that the materials required for a jetty are a 5.7% of total port materials and that the inventory of the construction of a trench [31] for an ammonia pipe are a 75% of the construction of a trench for ammonia and water, based on [31]. Also, the inventory of the construction of an ammonia storage facility was taken from the Ecoinvent Database [35]. For the case studies developed for Antofagasta, the impacts of the alkaline electrolyzer and the impact of the construction of the photovoltaic plants were also considered and based on [35, 36].

The life cycle impact assessment was performed using the Environmental Footprint 3.1 methodology. This methodology was chosen because it is compliant with the ISO EN15804 +A2 standard and because there are environmental thresholds documented in literature that are compliant with this method.

After the calculation of the environmental impact, we calculated the allocated share of environmental threshold or carrying capacity. Global environmental carrying capacities show the maximum allowable burdens of each protected area or environmental indicator and are documented as planetary boundaries [37].

There are several principles used to allocate environmental limits to a system. It is important to note that this allocation is inherently subjective, as it essentially involves

sharing a scarce resource (the environmental threshold) among individual societal activities (products, etc.) and there is not one objectively correct way to do this. For this study we used the Economic Value Added sharing principle. This principle allocates the share of the environmental burden of a product according to its price. To this purpose, we used the cost figures for construction and operations of projects in a region in each case study, as further explained in the Quantitative Findings section and in online supplementary material [27].

Results: Qualitative Findings

The findings below represent the view of the interviewed stakeholders and the documents that were analyzed. They therefore necessarily present a synthesis of subjective views and are not intended to reflect objective truths.

Global Developments

Chilean and international respondents alike express that the enthusiasm that existed earlier this decade has transformed to what has been called ¨a sense of realism¨. It is not expected that all 77 projects announced in Chile until August 2025 [12] will materialize, and many are not expected to follow the initially announced timelines. The production and export targets formulated in Chile´s 2020 national strategy are increasingly unlikely to be met, in concordance with reduced use and import ambitions in Europe, Japan, and elsewhere [4,22]. Europe and East Asia continue to pursue their net zero strategies and are the off take areas for GH2 derivatives, while the United States has put developments on hold. Europe and East Asia have also reduced the pace of developments and placed more emphasis on local GH2 production coupled with domestic off take in the short term [23, 24]. Many respondents expressed that the global political developments have become less favorable.

Nevertheless, the projects that are advancing are considered to be *¨more serious¨* and *¨more realistic¨*. The first very large ammonia carriers (VLACs) are being ordered, and while original off take opportunities in heavy industry may be less promising, applications in maritime logistics and aviation are perceived to be gaining momentum. For Chile, this may especially apply to scope 3 requirements for the carbon footprint of the mining industry. While there are no large off take agreements in place, the expectation is that the GH2 industry advances albeit somewhat slower than initially anticipated. While perhaps not a front runner anymore, Chile continues to be viewed to have a strategic advantage as a low cost provider country of GH2 and derivatives for off take countries seeking energy security through value chains that are respectful of social and environmental sustainability.

Views on National Developments

While any delays in Chilean developments thus appear to align with global trends, respondents also perceive barriers of a domestic nature. Developments are perceived to be more favorable elsewhere, with more enablers and less barriers. The ¨permisología¨ is often mentioned as a barrier, and several respondents mention the complexity and time-consuming EIA applications.

Another perceived barrier, which may also be viewed as a lacking enabler, is the absence of domestic GH2 and GNH3 demand. As other countries actively stimulate local production and off take, this was perceived to be less effective in Chile. While local off take by existing industries is hardly a possibility in the Magallanes region, the Antofagasta and Atacama regions together are host to more than half of the Chilean mining industry. The mining industry is an important driver of Chilean greenhouse gas emissions, yet the uptake of GH2 based opportunities to decarbonize is not perceived to promote GH2 projects as much as expected by some stakeholders.

Respondents view advancements in domestic off take more limited in Chile than elsewhere and partially attribute this to public efforts being more (pro)active and effective elsewhere. Some countries are perceived to have more generous financial arrangements in place, for instance in the form of subsidies or guarantees. International respondents provide examples of financial arrangements at scales that might better match the large investments sums of the GH2 value chain projects. The resources limitations of the Chilean government make it more challenging to provide such arrangements in comparison to large, industrialized, countries such as Australia, Japan, Germany, or the European Union. The more recent initiatives, such as tax-credits, are seen positively but are still in the implementation/legislative stage.

In addition to financial incentives, national and local governments can take other stimulating and coordinating roles. Many respondents perceive Chilean public actors to be less prone to actively coordinate regional developments beyond the project level. An active coordinating role is seen as necessary to solve the often mentioned *¨Chicken & Egg¨* problem: no demand → no supply → no demand → …., which private stakeholders by themselves appear to be unable to resolve. The international stakeholders provide examples of public entities coordination the development of GH2 infrastructure in ports, logistic infrastructure such as pipelines, or even public private joint ventures to advance the development of an electrolyzer or an ammonia cracker. Such activities to facilitate the development of regional GH2 networks may also alleviate the process of acquiring all necessary approvals and permits for private entities, as part of the infrastructure is brought in place by public actors. Such public engagement, possibly in the form of public private partnerships, may also serve to reduce the investment amounts and risks. The “Pacto de Magallanes” provides an interesting blue-print for future exploration of deeper public-private partnerships. The relevance of important state owned enterprises in Magallanes (ENAP) and Antofagasta (CODELCO) also provides an interesting space for this collaboration.

What GH2 Value Chain Infrastructure can be shared?

The NGH3 export value chain graph provided in Figure 1 describes many of the GH2 projects in Chile. The red components show the production infrastructure formed by the primary value adding operations: energy production, electrolysis, synthesis. The

desalination of water is a secondary production process. All Chilean respondents representing GH2 projects considered these production activities to be critical and to be core business, *¨No water, no H2¨*. While all respondents' projects in Antofagasta or Magallanes recognized the possibility to share infrastructure for primary operations or for desalination, no project appeared to consider sharing infrastructure for their core business. Chilean projects tightly coupled electrolysis and ammonia synthesis operations and plan for short on-site H2 pipelines. No shared H2 networks were mentioned. This contrasted with examples provided by international respondents.

The green components in Figure 1 refer to logistic activities, such as the transport and storage of electricity, GH2, and GNH3. Respondents commonly had considered sharing infrastructure for these operations but the disadvantages were typically considered to outweigh the benefits for now. For example, use of public electricity infrastructure in Antofagasta was associated with supply security risks.

To avoid risks with environmental assessments (EIA) and investments decisions (FID), the three GNH3 export projects that have submitted an EIA application so far have included their own ports and corresponding GNH3 storage and pipelines [21]. Especially in the Antofagasta region such dedicated infrastructure can be developed by repurposing or retrofitting existing port infrastructure, as is the case for the GNH3 export projects in the region that already submitted an EIA application. More generally, respondents often mentioned conversations about sharing of port infrastructure and efforts to sign corresponding agreements. The medium scale project HIF in the Magallanes region which aims to export eFuels is envisioned to use existing port infrastructure of ENAP.

The Inter American Development Bank has issued a study on developing a new, shared NGH3 export port in the Antofagasta region [9]. A recent Work Bank report on shared GH2 infrastructure also explicitly includes Chilean examples [25].

The quantitative case study on the Magallanes region is developed around the concept of sharing port infrastructure. While other studies tend to focus on the economics aspects of infrastructure sharing, this quantitative case study also recognizes social and environmental impacts of infrastructure sharing. These dimensions were also addressed in the interviews and respondents recognized sharing of infrastructure to be beneficial to reduce negative social and environmental impact. *¨Me parece que la pregunta por la infraestructura compartida tiene mucho sentido en términos de eficiencia,…. pero también de sustentabilidad.¨* However, the perceptions about the impact of infrastructure sharing often remained rather general: *¨the smaller the footprint, the better¨*.

From a societal perspective, the main concerns in the Magallanes region regarded the inflow of a large workforce of (potentially tens of) thousands, as needed to construct all planned projects. This temporary migration might have a severe impact on social structures, both in the scarcely populated areas in which the projects are planned to be developed, as for the Magallanes region in general. Both in Magallanes and in Antofagasta there were also

considerations about the impact on local communities whose livelihoods might, for instance, depend on fishing in locations affected by port operations of GNH3 export value chains.

Social and environmental project impacts were perceived to be very extensively addressed in the EIA applications. The combined impacts of multiple projects, however, were not perceived to be addressed, nor was this the case for sharing of infrastructure among projects. Many respondents in the Antofagasta region mentioned previous lack of infrastructure sharing by the mining industry as an example having negatively impacted regional development. Some viewed the disregard of opportunities for sharing as a culturally rooted tradition. Lack of *¨trust¨* and associated project risks were among the commonly mentioned barriers to sharing GH2 infrastructure.

While all respondents who represented projects showed a positive attitude towards infrastructure sharing, many of them also gave reasons that might cause to decide otherwise. These causes mostly related to risks. Risks associated with dependance on other projects that might not happen, be delayed, or change their mind, were commonly mentioned. For the Antofagasta region, respondents additionally mentioned the risk of depending on public electricity infrastructure.

Mitigating these risks by developing the project without sharing infrastructure was a natural alternative that promotes the likelihood of successful EIA application and a subsequent favorable final investment decision. For both regions this often caused projects to develop the full value chain close to a port, even when solar or wind energy generation further in land might be more efficient. This contrasts with international projects where energy generation was often decoupled from downstream value chain operations.

Altogether, the efforts to mitigate risks and comply with project level sustainability requirements were recognized to somewhat paradoxically discourage initiatives to share GH2 infrastructure, thus potentially foregoing resulting regional level sustainability gains. Reflections on this perception and on the qualitative findings in general will be provided in the final Discussion and Conclusion section of this report, after presenting the accompanying quantitative findings.

Results: Quantitative Findings

This quantitative findings section consists of three subsections. The first subsection addresses the economics, i.e., the business case, of infrastructure sharing, especially in relation to ports. This economic analysis underlies the subsequent social and environmental analysis in the form of an AESA. The second and third subsection develop case studies for infrastructure sharing in Magallanes and Antofagasta. The Magallanes case study is exclusively focused on export of GH2 derivatives. The Antofagasta case studies extents this export perspective towards domestic off take.

The Economics of Sharing Infrastructure among GNH3 Export Value Chains

For the time being, there are no realistic technologies for large scale sea transport of GH2 itself. Global value networks exchanging GH2 based energy are therefore mainly focused on GNH3 instead. A growing fleet of very large ammonia carriers (VLACs) is expected to be delivered across the globe in the coming years. The vast majority of the large scale GH2 value chains in Chile envision to export GNH3. Alternatively, the recently approved project HIF forms a variation in which GH2 is synthesized with carbons to form eFuels, which can be used for aviation and a wide variety of other end uses. Another important application is the aforementioned use of GNH3 as a fuel for maritime transport. For Chile this is especially of interest for Scope 3 decarbonization of the mining industry. Applications for the mining industry are explicitly developed in the Antofagasta case study.

The elaboration of shared infrastructure for GNH3 export value chains starts with an illustration of a fictitious 1 MT NH3 reference project. The operations of this reference project are modeled based on recent scientific literature and the corresponding model which includes all production and logistics operation in the value chain up to and including the port of exportation is publicly available [27]. The model also includes all corresponding costs and a snapshot of the model financials is provided in Table 1.

Item			CAPEX (€/a)	OPEX (€/a)	LCOA (€/t_NH3)	%
Water			703,878	258,315	1.2	0.2
Electrolysis			100,766,799	24,766,734	156.3	21.2
H2 Storage			7,242,652	682,759	9.9	1.3
Ammonia Synthesis			64,607,412	12,180,971	95.6	13.0
Ammonia Storage			5,729,555	2,700,601	10.5	1.4
Pipeline			867,524	245,342	1.4	0.2
Harbour			46,367,954	8,742,135	68.6	9.3
Energy Generation			244,950,201	53,156,737	371.2	50.3
Transmission Line			7,866,403	662,948	10.6	1.4
BESS			7,915,858	2,021,765	12.4	1.7
				TOTAL	**737.8**	**100.0**

Table 1: Financials of a reference 1MT NGH3 project

Figure 5 provides the corresponding levelized cost of Ammonia (LCOA) of 738 €/T. One may firstly observe that almost 90 percent of the costs are driven by the primary production operations, i.e. by the operations described as ¨core business¨ by respondents in the qualitative research. Recalling that sharing of infrastructure for these core operations was not being considered, the remaining business case for infrastructure sharing is limited to roughly 11 percent of total costs.

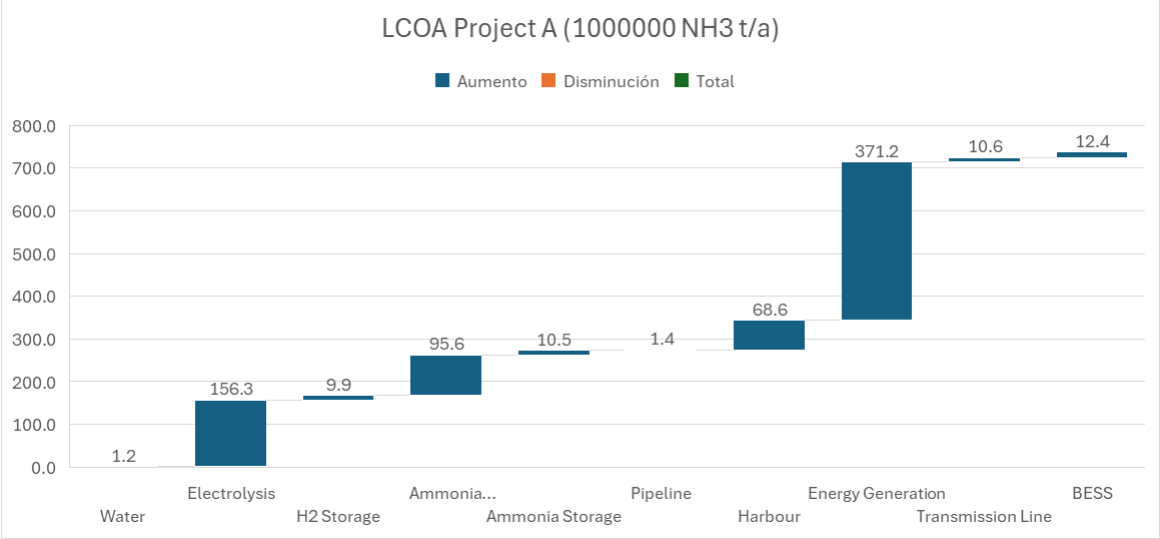


Figure 5: LCOA in €associated with the reference 1MT NGH3 project.

The relatively modest contribution of this remaining logistic infrastructure to total costs, and therefore the limited gains that may result from sharing logistic infrastructure, may partly explain why projects accept the cost of including this infrastructure in the project. Avoidance of collaboration and dependencies on other projects mitigates the external risks associated with these projects. In view of the substantial uncertainties regarding costs, prices, and demand volumes of the core business, mitigation of these logistics risks can be perceived as relatively affordable.

Port operations are far from core business for many of the GNH3 value chain investors and may well form an exception to the above line of reasoning. The IADB estimates the cost of a NH3 port to be well over 400 million euros [9], causing a port to contribute 8 percent of LCOH for the reference project when not shared. This observation forms the starting point for a more detailed analysis of the port operations required for a 1 MT NGH3 project and opportunities to share port infrastructure.

VLACS of 80.000 m3 capacity are expected to be the main mode of transportation for long distance transport when the global GNH3 value chains take off. This means that a 1MT

Project (roughly 180.000 kT GH2) fills 18 ships per year. Loading a VLAC takes less than 2 days, and 18 trips per year thus require less than 3 days of terminal time on average per month. A single VLAC terminal operating at 50 percent of capacity can therefore serve up to 5 MT of GNH3. Private terminals are estimated to be financed against a WACC of at least 10% [28-30]. Against a WACC of 10%, sharing a port with five projects of 1MT rather than having a port per project thus roughly reduces the contribution of port costs to LCOA from 55€ to 12€. Further reductions are possible at port locations which reliably admit port utilization rates of 60 percent and above, as is the case for some ports both in the Magallanes region area and in Antofagasta region (Mejillones).

When a shared port is owned by a public entity with a WACC of 7%, the CAPEX driven contribution of port costs to LCOA can be further reduced towards 8€. Publicly owned port owners such as ENAP and Codelco have both issued 10-years bonds and 30-years bonds in the 6-7 dividend range recently. Qualitative findings further suggest that public investment may additionally instill trust in private investors and serve to attract the projects needed to realize higher port utilization rates.

In Magallanes, several important ports belong to state-owned Empresa Portuaria Austral. Public company ENAP owns Muelle Laredo. There are also fully privately owned ports in Magallanes, such as Port Magallanes Otway. In Antofagasta, the port of Antofagasta is owned by the public company Empresa Portuaria Antofagasta which acts as a landlord (leases land and terminals). The nearby Mejillones port is privately owned by a subsidiary of state-owned mining company Codelco and operated using a landlord model. Most of the ports in the Antofagasta region are privately owned.

Ports from international benchmarks such as Pecem in Brazil and Rotterdam in The Netherlands are held by public entities acting as landlords. In The Netherlands and Australia, pipeline infrastructure for ammonia and hydrogen is in the hand of a state-owned enterprise which provides open access. Openness of access to shared infrastructure is a matter of policy and regulation. Private entities can also be regulated to provide open access.

When GH2 value chain projects share ports, they may need longer NGH3 pipelines to connect the production facilities to the port. Thus, the decrease in port costs may require an increase in the cost of other logistic infrastructure. The pipeline infrastructure can also be shared, which may reduce costs because of economies of scale. Two parallel ammonia pipelines with a capacity of 300 T/h each are more costly to build and operate than one pipeline with a capacity of 600 T/h. The pipeline itself is less than twice as expensive and additionally, there may be less than proportional additional costs associated with land use, safety measures, pumps, maintenance, etc. The (exponential) scaling factor for gas pipelines is estimated to be around 0.7 [31]. References on economies of scale in production operations are provided in [27].

Unless all infrastructure leading into the port and inside the port is proprietary, the sharing of a port requires all GNH3 flowing through the shared infrastructure to meet agreed standards. GNH3 can then be forwarded per kg and without molecule ownership (like electricity or water). This enables full sharing of pipelines and storage as necessary to capture the full cost benefits of port sharing.

Case Study Magallanes

Scenarios

The Magallanes region case study considers seven projects. Three projects have already applied for EIA and detailed public information is available for these projects on some of the key parameters of the value chains operations and costs. However, these applications don't fully disclose the relevant information. Moreover, the availability of information on the operations and costs of the other four projects is very limited. This case study therefore considers seven projects, each of which uses publicly available information from an actual project as much as possible, but none of these projects is claimed to be modelled accurately. To avoid any suggestion of representativeness, the case study projects have fictitious names.

The three projects that have already filed for EIA form ¨Ola 1¨ in the case study. The Ola 1 project by HIF project has already been approved. It is the only project which does not aim to produce NGH3 but instead aims to produce Methanol and other eFuels. The HIF project is therefore unable to share pipelines or storage infrastructure with any of the other projects considered in the case study. It will be represented by project M1A in the case study. In view of the case study focus on NGH3 and the lack of data on Methanol/eFuel operations and costs, results for project M1A are presented in terms of NGH3 equivalents. Because of the impossibilities of sharing infrastructure for these alternative products, the effects on economics are negligible for HIF anyway.

For the H2 project by TotalEnergies, the data are collected from the EIA application even while it is known that the project is being reoptimized. None of such reoptimization is yet considered in the project M1C. Project HNH, represented by M1B, is the third project of Ola 1. The EIA applications of H2 and HNH both include a dedicated port. Approximate locations of all projects and ports are indicated in Figure 6 below.

Figure 6: Approximate locations of projects and ports in the Magallanes region.

Of the remaining projects announced, for example via H2Vmagallanes.cl or H2Chile.cl, four projects were considered likely to advance and submit for EIA in the coming years, based on expert input. These four projects form ¨Ola 2¨ in the case study, and are referred to as M2D, M2E, M2F, and M2G. As mentioned, data availability is rather limited for Ola 2 projects and their modeling is therefore largely based on scientific literature.

Among the Ola 2 projects is project ¨Gente Grande¨by TEG. This project is the only project located in Tierra del Fuego. No plans have been published to build logistic infrastructure to connect projects in Tierra del Fuego with infrastructure in mainland Patagonia, e.g. via pipelines under the Straight of Magallanes. As it is doubtful whether such NGH3 pipelines would receive environmental approval, the case study does not consider infrastructure sharing by project M2G.

All costs for port infrastructure are taken from [9] in order to avoid that the impact of infrastructure sharing results from inconsistencies in the cost estimates for storage tanks, jetties, et cetera. This report [9] considers the construction of a completely new port and therefore has a 26 percent overhead cost to cater for project management costs and contingencies. The case study also considers the retrofitting of an existing port in the Otway Sound - referred to as OTW - and the extension of the ENAP owned port at Cabo Negro – referred to as CN. For the retrofitting and extensions of these existing ports, only ten percent of contingencies are considered. The weighted average cost of capital is set at seven percent for ENAP, and ten percent for all other ports, which are privately owned.

The case study scenarios for Ola2 assume project M2D (EdF) to use the Cabo Negro port of ENAP, and the project by Consortio (M2E) Austral to use the Otway port. Project M2E is in a

location where it doesn't have coastal access. Finally, project M2F (representing Nordex Acciona) which has coastal access is assumed to initially include a dedicated port.

The following scenarios are analyzed for Ola1.

Ola11: In this scenario there is no infrastructure sharing.
M1A uses port CN, M1B and M1C each with a dedicated port.

Ola12: In this scenario M1B and M1C share the port of M1B at San Gregorio (SG) which is likely to be developed earlier than any port for M1C. It requires the build pipeline infrastructure to connect M1C to SG.
M1A remains at CN.

Ola13: In this ¨grand coalition¨ scenario, the three projects share CN.
It requires constructing a new jetty and storage infrastructure at CN, in addition to pipelines from SG to CN.

Correspondingly, the next three scenarios also include Ola 2 and are defined as follows:

Ola21: Extends O11, no infrastructure sharing. M1A and M2D at CN, M2E at OTW, Other projects at dedicated port.

Ola22: Extends Ola 12. M1A and M2D at CN, M2E and M2F at OTW,
M1B a1C at SG.

Ola23: The ¨Grand Coalition¨ of all projects at CN, except M2G in Tierra del Fuego.
This requires a second jetty and set of storage tanks at CN.

Cost Allocation

The development of projects in two waves also has implications for the allocation of the cost of shared infrastructure. The calculation of Shapley values normally considers marginal costs changes of coalition forming, starting from single projects which subsequently form larger and larger coalitions until the grand coalition of all projects is reached, as explained in Figure 4. Accordingly, it considers all possible orders in which projects can form coalitions and averages marginal costs over all these orders.

The case study analysis, however, assumes all Ola 1projects to be implemented and possibly form first coalitions before Ola 2 projects emerge. This renders many orders of coalition forming to become irrelevant and to be disregarded in the analysis. In (future) reality, the

set of possible orders may be even more limited. The resulting LCOA are presented in Tables 2 and 3.

	Ola11	Ola12	Ola13
M1A	773	773	638
M1B	738	714	700
M1C	638	633	630

Table 2: LCOA for the three Ola1 scenarios in Magallanes

When reading Table 2 it is important to recall that the cost for M1A indicate a fictitious GNH3 cost. As this project is planned to be integrated in the ongoing operations of the CN port, it is not impacted by infrastructure sharing as elaborated in the scenarios. The relatively high LCOA simply reflects the modest scale of this first project to have obtained EIA approval.

	Ola 21	Ola 22	Ola 23
M1A	773	773	773
M1B	738	714	695
M1C	638	633	629
M2D	717	717	685
M2E	680	653	658
M2F	689	668	653
M2G	679	679	679

Table 3: LCOA for the three Ola2 scenarios in Magallanes

Especially M1B benefits from infrastructure sharing in Ola1. It can reduce LCOA by around 5%. The LCOA effect for M1C is smaller because the project produces a much larger volume than M1B. It therefore has more economies of scale without sharing infrastructure and the project level benefits of sharing are relatively smaller per ton.

Absolute Environmental Sustainability Assessment

The AESA contrasts the environmental burden of systems with the allocated share of the environmental limits or planetary boundaries. For this purpose, we first calculate the environmental impact of the construction of the required infrastructure shown in Table 4.

	Ola 11	Ola 1.2	Ola 1.3	Ola 2.1	Ola 2.2	Ola 2.3
New port (quantity)	2	1	0	4	2	1
New pipes (km)	141.7	222.7	209.7	337.6	354.4	328.3
New jetty (quantity)	0	0	1	1	1	2
Ammonia tanks (quantity)	0	0	2	2	4	4

Table 4: Required infrastructure for Ola1 and Ola2 in Magallanes

Figure 7 shows the standardized environmental impact for the case studies. It clearly shows that in value network designs in which one or more new ports are constructed, these new ports account for the main part of the environmental impacts. In general it conversely holds that longer pipelines are needed when there are less ports, whether newly constructed or otherwise. This causes the relative impact of pipes to become more significant.

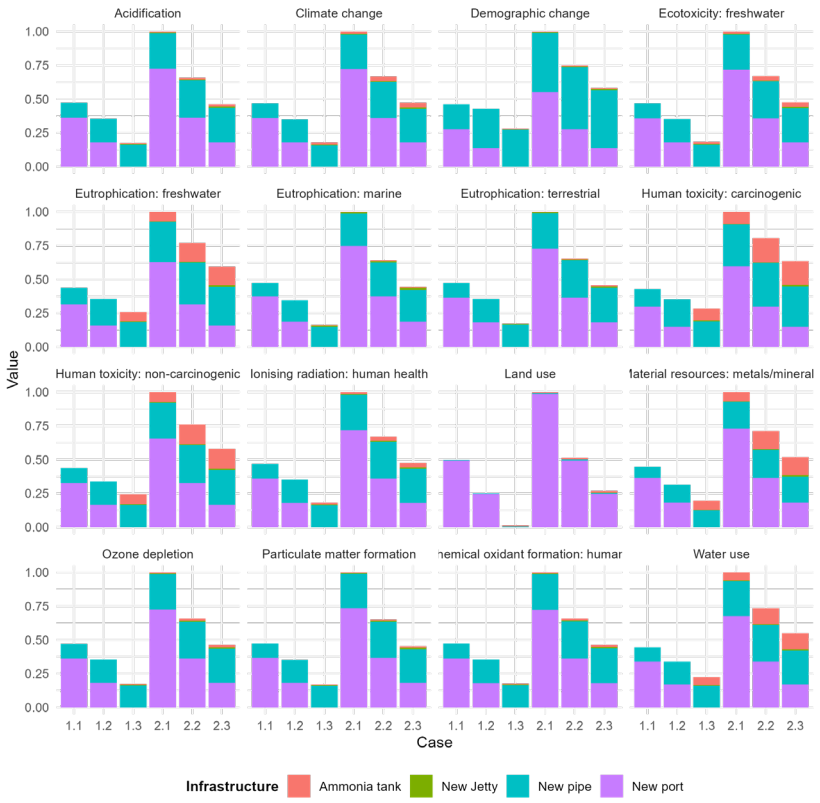


Figure 7: Standardized environmental impact of the six scenarios in the Magallanes case study

Another important finding from Figure 7 is that the environmental impact of the system reduces as there is more sharing i.e., from 1.1 to 1.2 and to 1.3 and from 2.1. to 2.2 to 2.3. It

is lowest in the Grand Coalition scenarios in which all projects share a single port. The environmental benefit of infrastructure sharing is more significant for the categories Marine Eutrophication and Land Use, because both of these metrics are driven by port construction.

Figure 8 shows the transgression level of the environmental limits allocated to the Ola1 projects M1A, M1B and M1C. It shows that not sharing infrastructure causes the planetary boundaries to be trespassed in five indicators: demographic change, marine eutrophication, terrestrial eutrophication, particulate matter formation and photochemical oxidant formation.

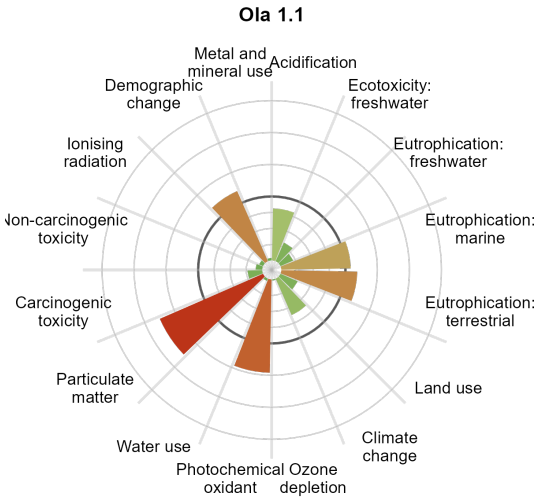
Demographic change is due to the immigration of workers for the construction of the new infrastructure. Marine eutrophication is caused by excessive nutrient inputs (i.e. nitrogen) to sea water, which can trigger algal blooms, oxygen depletion, and biodiversity loss. Similarly, terrestrial eutrophication results from atmospheric deposition of reactive nitrogen, which disrupts nutrient balances in soils and alters plant community composition. Particulate matter formation and photochemical oxidant formation are mainly due to the burning of diesel in the machinery used for the construction of the infrastructure.

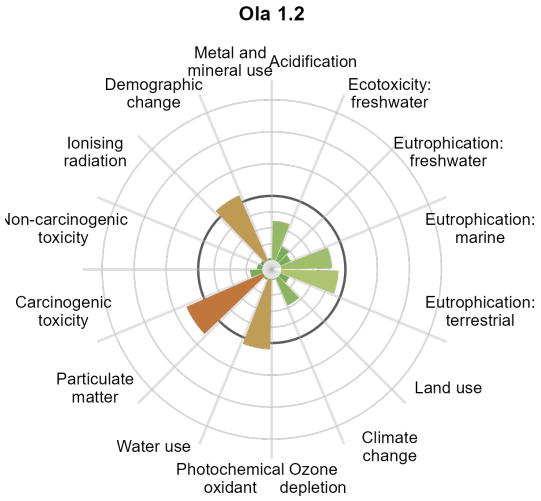
It can be seen that in case 1.2 and case 1.3 the environmental impact is reduced for all indicators. In Ola1, the grand coalition allows the three projects to operate within the planetary boundaries. In other words, sharing ports and pipes would transform the combined GH2 value chains to operate sustainably in absolute terms.

Figure 9 shows the social and environmental performance against the planetary boundaries in Magallanes when implementing Ola2, i.e., adding projects M2D, M2E, M2G to projects M1A, M1B, M1C. The Figure shows that if infrastructure is not shared, the operation of ports and pipes again transgress the five planetary boundaries: demographic change, marine eutrophication, terrestrial eutrophication, particulate matter formation and photochemical oxidant formation.

In scenario 2.2, M1A and M2D use port CN, M2E and M2F use OTW, and M1B and M1C use SG. This causes most environmental indicators to stay within the planetary boundaries.

Finally, in the case of the Grand Coalition, all environmental indicators stay within the safe operating space for the planet and humankind and are sustainable in absolute terms. However, the demographic change still trespasses the allocated boundary. This confirms the concerns of NGOs and government respondents expressed in the qualitative research. On the other hand, the social impact of these migration flows might be limited when the construction activities are spread out over a larger time period, in which case they might not coincide.





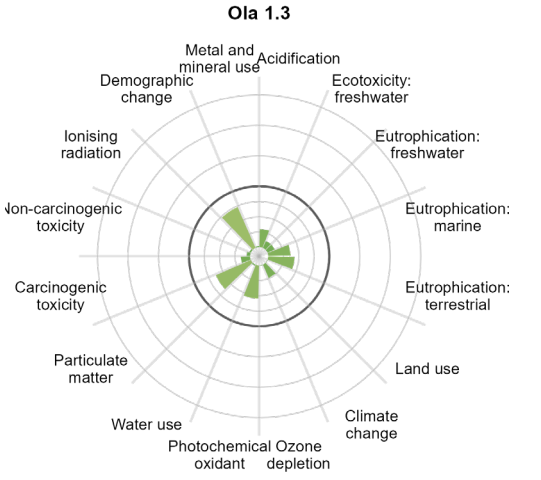
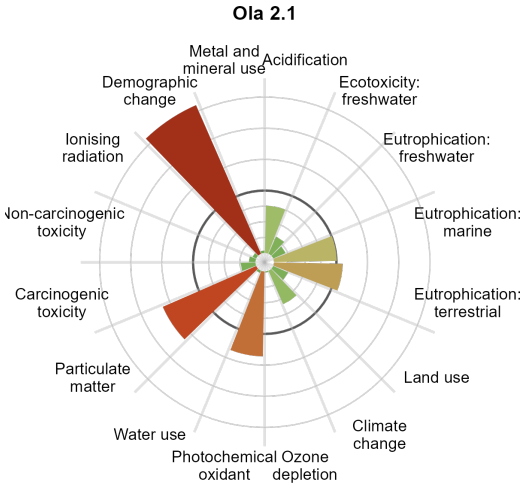
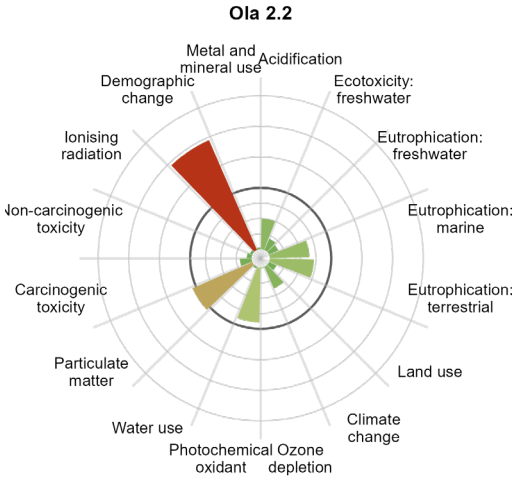


Figure 8: Social and environmental performance against the planetary boundaries for Ola1, Magallanes





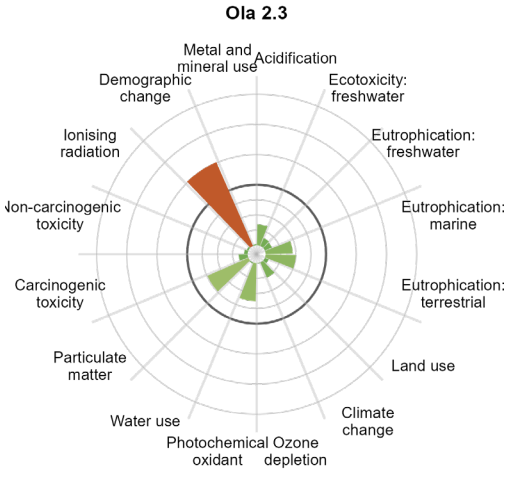


Figure 9: Social and environmental performance against the planetary boundaries for Ola2, Magallanes.

Case Study Antofagasta

¨pudiésemos tener un mercado local, sí, pero hay que desarrollar las industrias asociadas al encadenamiento productivo con eso, que es un trabajo superlindo y muy interesante¨

The Antofagasta region shares with the Magallanes region that is a globally competitive region for low-cost production of GH2 and derivatives. Together with the neighboring and more inland region of Atacama, it additionally hosts more than 60 percent of the Chilean mining industry and, more specifically of the Chilean copper mining industry. The energy intensive mining industry and its value chains presently have a considerable carbon footprint. They are therefore a focal point in Chile´s net zero strategy and mining companies have considerable carbon reduction ambitions in all three scopes, i.e., with their own operations, energy supplied, and with other partners in the value chain such as for maritime logistics. This Antofagasta case study thus importantly focus on domestic GH2 and derivatives off take by Chile´s mining industry and value chain partners.

Existing projects and GNH3 Export

The case study is firstly built on existing projects, which are again partitioned into two waves, ¨Ola1¨and ¨Ola2¨. Ola1 considers the projects by Susterra (A1A), MAE (A1B), and INNA (A1C), which have already filed for EIA approval. In fact, the mining oriented project A1A in Calama has already received SEIA approval. Calama is more than 250 KM by road from Mejillones, where project A1B is located near the ports. Project A1C is some 300 kilometers to the South, along the cost, near Taltal. Given these distances, the scales of the projects, and the fact that the City of Antofagasta lies between Taltal and Mejillones, the opportunities for infrastructure sharing among the Ola1 projects appear non existent and are henceforth disregarded. Following the EIA applications, project A1B is modeled to join an existing port and project A1C is modeled to repurpose an existing port to export NGH3. Inland project A1A doesn't include a port.

Ola2 brings two more projects in Taltal, Amigos del Verano, and Faraday (A2D, A2E). There is little public information available about these projects. From the available information, it appears feasible and plausible for projects A2D an A2E to share a port with A1C. The export of the three projects together will not exceed 3.5 MT, which is easily within the capacity of a single jetty port. It is worth mentioning that the approval of projects in Taltal requires to resolve an additional complexity related to the nearby astronomy research activities.

Based on expert input, we further define Ola2 to include projects Hyex II, Hoasis, and Solar Amonia in the Mejillones region (A2F, A2G. A2H). Following public information, A2F is envisioned to supply NGH3 and GH2 for domestic use. It is designed to provide all of the roughly 350 kT of ammonia ENAEX uses per year to produce explosives for the mining industry. The remaining 350 kT of GNH3 produced by A2F, as well as the 250 KT NGH3 production planned for A2G and 320 kT planned for A2H can easily be exported within the capacity of the single jetty port adapted by A1B in Ola1 for GH3 exportation in Mejillones. Thus, next to each project having its own part, we only consider a second scenario in which all projects in Taltal share the port of A1C and all Mejillones projects share the port of A1B. The resulting LCOA are depicted in Table 5.*

Location	Project	Dedicated Port	Shared Port
Taltal	**A1C**	761	711
	A1D	819	770
	A1E	847	785
Mejillones	**A1B**	835	802
	A1F	965	905
	A1G	1057	888
	A1H	991	859

Table 5: LCOA Ola2 With and without shared ports in the Antofagasta region

As was the case for the analysis in Magallanes, there are clear benefits of sharing an existing port over constructing a port for the Ola 2 projects. Moreover, with these Ola2 projects joining the ports of the Ola1 projects, the LCOA for the Ola1 projects also improves by a comparable amount, depending on project size.

Absolute Environmental Sustainability Assessment

Table 6 shows the total infrastructure required for Ola 1 and Ola 2 projects when not sharing and sharing a port.

	Ola 1	Ola2
New port (quantity)	6	1
New pipes (km)	148	140
New Storage tanks	4	4
Jetty retrofit	1	1

Table 6: Infrastructure requirements for Ola 1 and Ola 2 project in Antofagasta

Figure 10 shows the standardized environmental impact for when a dedicated port is constructed and when the port is shared. As was the case in Magallanes, in value network designs in which a dedicated port for each case study is constructed, the new ports account for the main part of the environmental impacts. Moreover, the port impact dominates the pipe impact, for which the differences are small as all projects are relatively nearby the shared port.

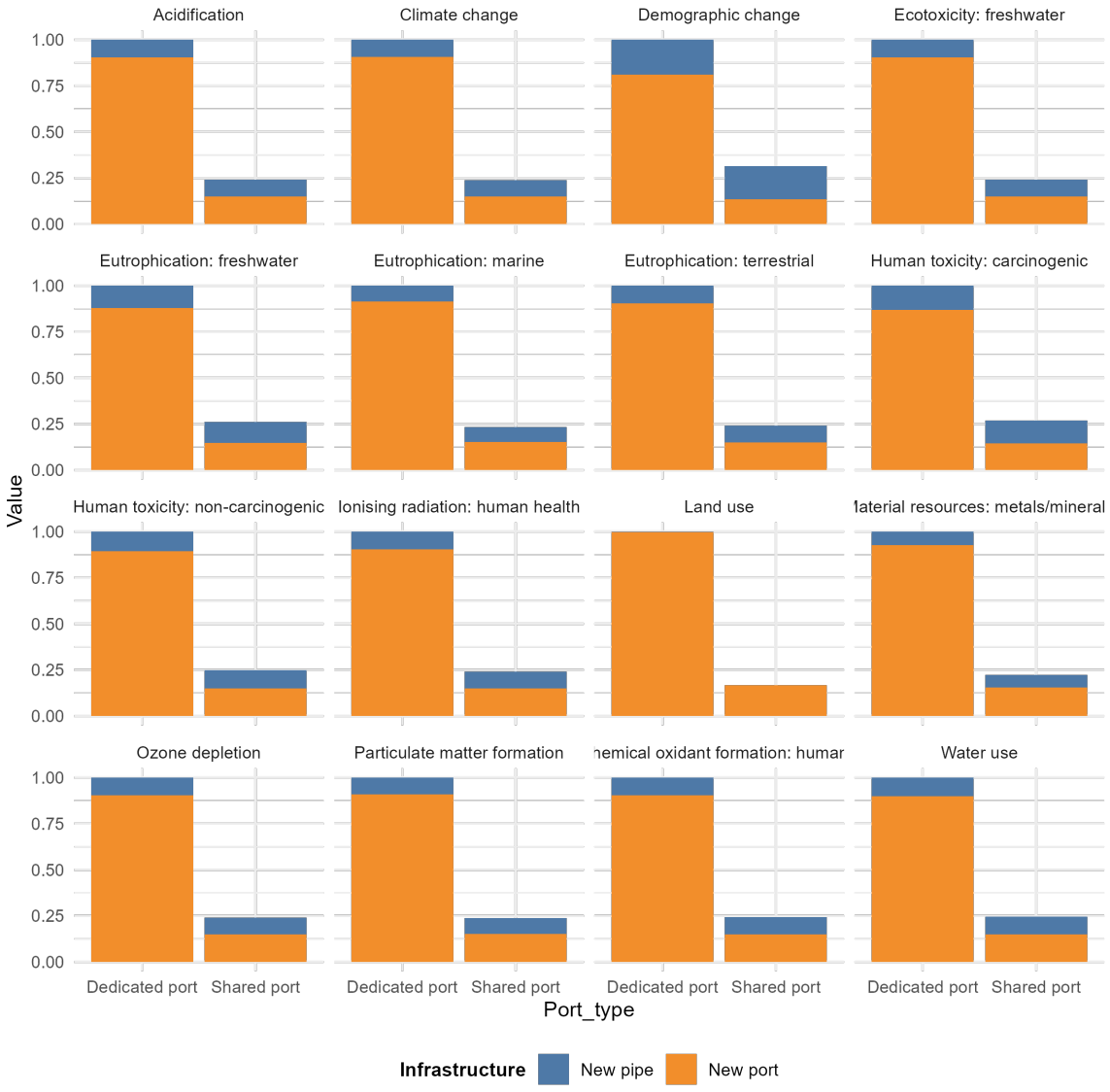


Figure 10: Standardized environmental impacts for Ola 1 and Ola 2 Antofagasta.

Figure 11 shows the social and environmental performance against the planetary boundaries in Antofagasta when implementing Ola2, i.e., when implementing A1C, A1D, A1E in Mejillones and A1B, A1F, A1g, A1H in Taltal. The Figure shows that if infrastructure is not shared, the

operation of ports and pipes again transgress five planetary boundaries: acidification, marine eutrophication, terrestrial eutrophication, particulate matter formation and photochemical oxidant formation. However, when a port is shared the operation stays within the planetary boundaries.

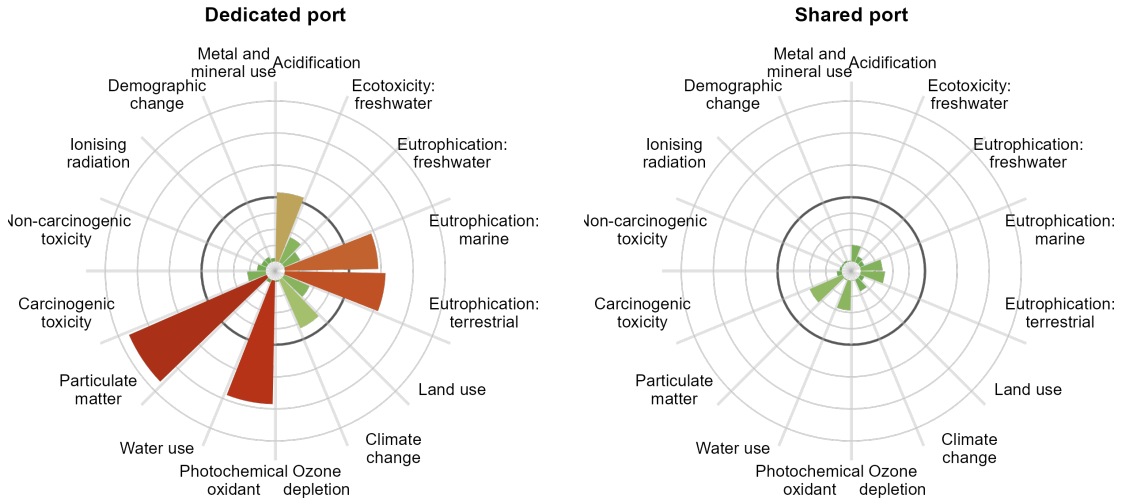


Figure 11: Social and environmental performance against the planetary boundaries for Ola1 and Ola2, Antofagasta.

Domestic Off Take

The remainder of this Antofagasta case study focusses on shared infrastructure for domestic off take by the mining industry and its value chains. To this purpose, the case study introduces an ¨Ola3¨ with projects that bear no relationship with Ola1 and Ola2 projects. More specifically, Ola3 acknowledges that project A1A represents the already approved Susterra projects which envisions to provide GH2 to replace diesel as a fuel for trucks that transport copper by truck (or train) from the mines to the ports and other destinations and that project A2F (Enaex) plans to produce GNH3 as a raw material for explosives used in the mining industry. The Ola3 projects therefore focus on the supply of GH2 and GNH3 for the following alternative local off take use cases related to the mining industry:

1. Fuel for transportation by sea and land of fossil fuels to provide the necessary feedstock for the mining industry.
2. As a fuel for CAEX and other machines in the mines.
3. As a feedstock for smelting in copper foundries,
4. As a fuel for outbound ships exporting copper products. This use case is referred to as bunkering. Bunkering requires an infrastructure that is similar to NGH3 export infrastructure when taking place in a port. It can also be performed in open sea.

The first use case is disregarded in the remainder as it no longer applies when covering demand for use cases 2-4 and projects A1A and A2F.

To optimize cost together with social and environmental impact, the Ola3 projects considered seek to maximally explore opportunities for shared infrastructure. They share infrastructure across mining companies, across geographical areas, and across the three use cases, as is further elaborated below.

Cluster		Mines	Main Ports Used	# CAEX GH2	KT Copper 2024
Escondida		Escondida	Puerto Coloso, Puerto de Antofagasta	95	1278
		Zaldívar			83
Calama Norte		Chuquicamata	Puerto Mejillones (Angamos)	140	289
		Radomiro Tomic			270
Sierra Gorda		Sierra Gorda	Puerto de Antofagasta	80	155
		Centinela (Súlfuros)			122
		Centinela (Óxidos)			102

Table 7: The three copper mine clusters in Antofagasta and Atacama in the case study.

Bearing in mind that the focus is on sharing of infrastructure and that no detailed publicly available exist on energy use per mine, foundry or ship, the scenarios are elaborated on the basis of three clusters of copper mines that together capture 2.3 MT of the almost 3.5 MT of copper products exported from the Antofagasta and Atacama regions annually [32]. The clusters are ¨Escondida¨, ¨Calama Norte¨, and ¨Sierra Gorda¨ as visualized in Figure 12. The mines in these clusters are depicted in Table 7, together with their production volumes and an estimate of the number of CAEX in these clusters that might be fueled by GH2 in the medium-term future. The CAEX estimates are based on expert input and assume that for half of the CAEX it is preferable to electrify rather than to substitute the fossil fuel Diesel for GH2.

Table 7 provides distances between clusters and distances to the nearest port. Cluster Calama Norte is dominated by Codelco which also operates a foundry in the region. Another foundry (operated by Glencore) is to the south of Antofagasta, between the Escondida Cluster and the coast, as is depicted in Figure 10.

In the remainder we assume that the Antofagasta ports, which lie well within the city, are not suited for GNH3 storage, bunkering, or loading for reasons of safety. While Ola1 and Ola2 imply one or more ports in Mejillones will be operating GNH3 by the time Ola3 is implemented, this is not the case for Puerto Coloso. Hence, we assume all bunkering happens in or via a Mejillones port.

From To	Puerto Coloso	Mejillones	Antofagasta	Sierra Gorda
Escondida	200			326
Calama Norte		255		70
Sierra Gorda		185	150	

Table 8. Distances between mining clusters and ports

Based on current daily use of Diesel above 3000 liters, the daily GH2 consumption per CAEX is estimated at 1T, and annual demand per CAEX at 365T. Based on energy equivalence, the annual demand for GH2 of a smelter, when substituting fossil fuels is estimated at 7500 T. The NGH3 demand for ships delivering Chilean copper are estimated using the model in the online Appendix. With an average load of 50 Kt, the region sends the equivalent of more than 70 ships of copper overseas, half of which with destination China [32]. This amounts to an NGH3 consumption of more than 500 Kt, which is the equivalent of 89 Kt of GH2, plus the GH2 required as energy for the Haber-Bosch process. Table 9 presents details on the GH2 demand for each of the use cases for each of the clusters. If ships from other mines also switch to GNH3, total demand for bunkering rises by up to 35 Kt GH2. Altogether we conservatively estimate total GH2 demand for the use cases 3,4 and 5 at 200 GH2, of which 130 Kt for mining and foundries, and 70 Kt for bunkering.

Cluster	Demand CAEX	Demand Smelting	Demand Sea Transport	Total
Escondida	34675	7500*	36400	78575
Calama Norte	51100	7500	15400	74000
Sierra Gorda	29200		7700	36900

Table 9. Demand per use case and total demand per cluster. The Foundry in La Negra is allocated along the pipeline to Cluster Escondida. Sea transport demand is presented in GH2 needed for the corresponding GNH3.

In **Ola3 scenario 1**, a new project A1X produces 130 Kt GH2 in Calama. Given the high capacity pipelines already in place to transport ocean water to the mines and the relatively minor demand of an electrolyzer plant compared to the mines (a few percent), we assume no additional water pipelines and desalination facilities are needed. The GH2 produced by A1X in Calama is transported via pipelines to the Sierra Gorda cluster, the Foundry in La Negra, and the Escondida cluster (see Figure 12). Considering the project as a joint effort (if not joint venture) between the mining companies involved, the cost of GH2 is equalized across all mines and foundries regardless of distance to the electrolyzer. Project A1X could be an extension of the much smaller project A1A but this scenario is not explicitly modelled.

Still in Ola3 scenario 1, a second project A1Y produces 340 Kt NGH3 in Mejillones, for bunkering from a dedicated solar plant. Electrolyzer, and Haber Bosch plant, and a dedicated jetty for bunkering in an existing port.

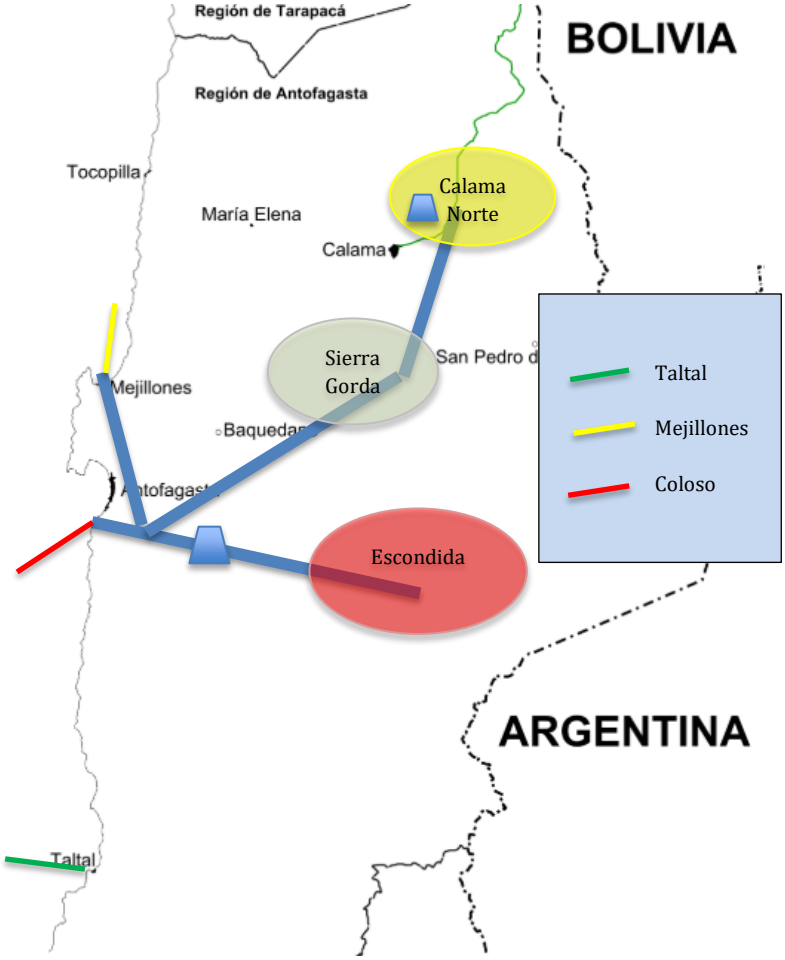


Figure 12 Geography of mining clusters, foundries and ports in Antofagasta and Atacama.

Scenario 2 for Ola3 differs from scenario 1 in the sense that A1Y now receives GH2 from A1X. Hence there is no need for a dedicated solar plant nor for an electrolyzer. However, the GH2 pipeline infrastructure from Scenario 1 has to be extended to Mejillones (see Figure 12), The additional cost and environmental burden of these additional pipelines may be counterbalanced by increased efficiency of the solar plant in Calama and the electrolyzer.

Lastly, **Scenario 3 in Ola3**, eliminates project A1Y altogether and enlarges the Ola2 Haber Bosch facility of A2F - which is already importantly focused on serving derivatives demand by the mining industry - to accommodate the 340 Kt GNH3 production for bunkering from

GH2 supplied from A1X. This scenario benefits from economies of scale resulting from sharing the Haber Bosch production infrastructure.

Impact analysis for Domestic Off Take Scenarios

Table 10 shows important infrastructure requirements for Ola3 as required to calculate the cost and the social and environmental impact.

	Scenario 1	Scenario 2	Scenario 3
New pipes (km)	406	456	456
Hydrogen tanks (quantity)	2	2	2
Electrolyzer - equivalents to 118 H2/hr	187	187	187
Solar plant - Equivalent to a 570 kWp plant	5572	5378	5378

Table 10: Required infrastructure for Ola3

The cost of GH2 for the mines and the foundries and of GNH3 for bunkering in the three scenarios are depicted in Table 11. These prices include delivery of LCOH to central storage tanks in the clusters. The cost reductions achievable are again substantial, also for the Ola2 project A2F. One may further notice that an LCOH of 3.29 € would imply a price of energy that is close to current industrial prices for diesel in Chile.

	Scenario 1	Scenario 2	Scenario 3
LCOH (€/kg)	3.73	3.37	3.29
LCOA A1Y (€/T)	885	884	854
LCOA A2F	965	965	936

Table 11: LCOH and LCOA for Ola3 scenarios (without sharing of port infrastructure)

When analyzing the environmental impacts, the results differ in less than 5%, for all environmental indicators between scenario 1 and scenario 2. This can be explained by the relative absence of ecologies of scale for solar panels and electrolyzers. The environmental impact of sharing a Haber Bosch facility in scenario 3 is not separately modeled.

Discussion and Conclusions

In Chile and across the globe, GH2 projects advance. Domestic and national stakeholders agree that the advancements are not according to the optimistic timelines proposed in the early years of the present decennium. However, extant projects are considered to be more serious and more realistic, as is also evidenced by the fact that both in the Magallanes region and in the Antofagasta region, a first project has received SEIA approval. Moreover, two large scale applications are in advances stages of application, and the combined value of projects in the pipeline is estimated to be around 40 billion euros.

The far majority of these projects plan to produce and export GNH3. While the demand and transportation modalities are still uncertain, their underlying value proposition is rooted in Chile´s global competitive advantage as a reliable, lowest cost provider of GH2 and derivatives, with socially and environmentally sustainable value chain operations. Our findings indicate that the planned large-scale projects face many challenges to turn this value proposition into reality. Moreover, it shows that sharing of GH2 infrastructure brings challenges that can form barriers, but can ultimately strengthen the projects from economic, social, and environmental perspectives. The latter not only applies to GNH3 export value chains but also to GH2 value chains to provision domestic demand and help Chile and its mining industry achieve its climate goals.

Getting a single large scale GH2 value chain project approved is already a costly, time consuming, and complex task, causing many project developers to seek simplicity and to mitigate risk. Risks may arise from dependencies on other private or public partners whose projects may change, be postponed, or cancelled altogether, thus negatively impacting the feasibility and return on investments of projects. Such considerations tend to lead to self-contained project designs, with little sharing of infrastructure, even if this entails sacrificing economies of scale and scope as attainable by infrastructure sharing.

Proactive and trustworthy public entities such as Corfo which promote partnerships and invest in infrastructure for common use can help overcome these barriers to infrastructure sharing. This may lead to lower total investments required and at a lower weighted average cost of capital. The Magallanes case study provides various regional value network configurations leveraging such public private infrastructure sharing worthy of consideration to strengthen the business cases while mitigating risks.

As a global trend, many countries currently attach more priority to domestic value chains, stimulating local demand and local production. This may reduce short- and medium-term demand for Chilean GH2 derivates and invites Chile to prioritize alternatives for GNH3 export. These alternatives exist in the form of developing GH2 based fuels for maritime and aviation logistics and in forming domestic value chains by stimulating local demand and match it with local supply. For instance, Chile holds a potential competitive edge as a provider of green copper.

While there are still many challenges around local demand, the current government initiatives to stimulate domestic demand may strengthen and deepen Chile´s global position as a GH2 provider. Our case study for the Antofagasta region shows the advantages of infrastructure sharing between various private and public partners, and among local demand use cases in mining, foundries, and maritime logistics, which can even share infrastructure with GNH3 export value chains. Organisations such as H2 Antofagasta that bring these partners together can help instill trust and facilitate collaboration and sharing of infrastructure.

While the above considers economic perspectives that might be top of mind for the private investors weighing the economic perspectives of multibillion dollar projects in Chile, one may argue that the social and environmental impacts GH2 value chains may have in the Antofagasta and Magallanes regions are even more important. These regard possible biodiversity loss, loss of livelihood for local communities, ocean eutroficacion, and all other boundaries of a safe operating space for humankind and planet Earth. It is imperative that GH2 projects motivated by the ambition to prevent the transgression of the global climate change boundaries avoid local boundary transgressions on other dimensions. Our findings clearly indicate that infrastructure sharing is necessary to ensure global and local boundaries are both respected. Without infrastructure sharing, planned projects may be expected to transgress local boundaries for demographic change, marine eutrophication, terrestrial eutrophication, particulate matter formation and photochemical oxidant formation, while this can be largely or even fully prevented by sharing infrastructure. We note that this may occur even when individual projects meet the criteria for SEIA approval.

Infrastructure sharing and public private partnerships in energy value networks is not new. However, for the newly arising green hydrogen economy, the best practices are only starting to develop. Our respondents perceive that Chile may no longer be at the forefront of global best practices. The Antafagasta case study provides innovative examples suggesting how infrastructure sharing can extend beyond ports and pipelines, to bunkering facilities, Haber Bosch plants, and ultimately the full value chain.

The Chilean government and public entities are increasingly taking initiatives to promote the GH2 industry and infrastructure sharing as suggested by the stakeholders interviewed for this research. Additional financial incentives have been announced during the course of this research, and the ¨Pacto de Magallanes¨ forms a government led initiative that provides an interesting blueprint to explore future, deeper, public-private partnerships. Other instruments, such as regional logistic development plans may serve as valuable complements in support of reaping the benefits of infrastructure sharing [26]. State-owned enterprises such as CODELCO (Antofagasta) and ENAP (Magallanes) are already assuming important roles and the case studies highlight that they can form main drivers of regional infrastructure sharing. As public entities, they are especially well positioned to help guide

economic advancements within the social and environmental boundaries of Chile and its Antofagasta and Magallanes regions.

The recent World Bank on shared infrastructure for clean Hydrogen already showcases Chilean shared infrastructure [25]. This research explores future improvements in this direction. As all modeled projects, plants, pipelines and ports only partially model reality, the analyses results should not be interpreted as proposals. They are not exhaustive, and it is likely that better alternative infrastructure sharing configurations emerge as the regions advance.

However, the scenarios analyzed are realistic enough to consider the outcomes of the quantitative case studies as credible evidence that infrastructure sharing can be beneficial from all three of the economic, social, and environmental perspectives. Together with the qualitative findings, they may instill trust among public and private stakeholders that infrastructure sharing can strengthen the position of Chilean projects as responsible and dependable providers of lowest cost GH2 and derivatives. As the results also strongly suggest infrastructure sharing is necessary to advance GH2 projects, the findings may serve to assist all stakeholders involved to align on realistic next steps and together position Chile sustainably at the forefront of global developments.

References

1. Hydrogen Production and Infrastructure Database, International Energy Agency, Accessed October 11, 2025, www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database#hydrogen-production-projects
2. Panel Control Operación 25 septiembre 2025 versión pública, Coordinador Nacional Electrico, 2025, Accessed October 11, 2025, www.coordinador.cl/wp-content/uploads/2025/10/Panel-de-Operacion-publico_25-Septiembre_2025.pdf
3. https://seia.sea.gob.cl/busqueda/buscarProyectoResumen.php Accessed October 12, 2025.
4. National Green Hydrogen Strategy, 2020, Max Correa A. – Carlos Barría Q. – Benjamín Maluenda P., Editors, Ministry of Energy, Chile.
5. Planetary boundaries: Guiding human development on a changing planet., 2015, Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Sörlin, S. Science, 347(6223), 1259855.
6. Planetary boundaries: exploring the safe operating space for humanity, 2009, Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Foley, J., Ecology and society, 14(2).
7. Yin, R. K. (2015). Qualitative research from start to finish. Guilford publications.
8. https://www.h2vmagallanes.cl/ accessed June-October 2025
9. Inter-American Development Bank, 2022, Pre-feasiblity for a Hydrogen Export Project, Final Report
10. https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database, accessed May-October 2025
11. Integrated description of projects for generation of green hydrogen., SEA Chile. Environmental Assessment criteria (SEIA), accessed October 9, 2025, https://www.sea.gob.cl/en/noticias/sea-publica-nuevo-criterio-de-evaluacion-ambiental-sobre-descripcion-integrada-de
12. https://h2chile.cl/mapa-de-proyectos/ accessed May-November 2025
13. Sustainable operations management, 2015, Kleindorfer, P. R., Singhal, K., & Van Wassenhove, L. N., Production and operations management, 14(4), 482-492.
14. Sustainable operations management: recent trends and future directions. 2014, Walker, P. H., Seuring, P. S., Sarkis, P. J., & Klassen, P. R., International Journal of Operations & Production Management, 34(5).
15. The Sustainability of Operations: Past, Present, Future., 2024, Joris van de Klundert
16. Winter, E. (2002). "The shapley value.": Handbook of game theory with economic applications 3.
17. Massol, O., Tchung-Ming, S., & Banal-Estañol, A. (2015). Joining the CCS club! The economics of CO2 pipeline projects. European Journal of Operational Research, 247(1), 259-275.

18. A game theory approach in hydrogen supply chain resilience: focus on pricing, sourcing, and transmission security, 2025, Rajabzadeh, H., Shaya, N., Shirafkan, N., et al. , Annals of Operations Research. url: https://link.springer.com/article/10.1007/s10479-025-06739-w
19. Life-cycle assessment to guide solutions for the triple planetary crisis. 2023, Hellweg, S., Benetto, E., Huijbregts, M. A., Verones, F., & Wood, R., Nature Reviews Earth & Environment, 4(7), 471-486.
20. Review of life-cycle based methods for absolute environmental sustainability assessment and their applications, 2020, A Bjørn, C Chandrakumar, AM Boulay, G Doka, K Fang, N Gondran, Environmental Research Letters 15 (8), 083001
21. https://www.sea.gob.cl/ accessed October, 2025
22. Umsetzung der Wasserstoffstrategie des Bundes, https://www.bundesrechnungshof.de/SharedDocs/Downloads/DE/Berichte/2025/wasserstoffstrategie-volltext.pdf?__blob=publicationFile&v=2, accessed October 2025.
23. Basic Hydrogen Strategy June 6, 2023 The Ministerial Council on Renewable Energy, Hydrogen and Related Issues, Japanes Government, https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf, accessed October 2025,
24. The Case for Recalibrating Europe's Hydrogen Strategy, March 10, 2025, https://rmi.org/the-case-for-re-calibrating-europes-hydrogen-strategy/, accessed October 2025.
25. "World Bank. 2025. Shared Infrastructure for Clean Hydrogen. Live Wire; 2025/145. © World Bank. http://hdl.handle.net/10986/43672 License: CC BY-NC 3.0 IGO." Accessed October 2025.
26. El Plan de Desarrollo Logístico de Magallanes y de la Antártica Chilena, 2024, https://logistica.mtt.cl/wp-content/uploads/2024/12/Documento-Plan-Desarrollo-Logistico-Magallanes-COMPLETO.pdf, accessed October 2025.
27. GH2 Value Chain model: https://www.researchgate.net/profile/Joris-Van-De-Klundert-3/research
28. The Cost of Capital in Clean Energy Transitions, https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions, Accessed August 2025
29. International Energy Agency, 2021, The Cost of Capital in Green Energy Transitions.
30. Lee, Moongyung, and Deger Saygin. 2023, Financing cost impacts on cost competitiveness of green hydrogen in emerging and developing economies." OECD Environment Working Papers
31. Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Feasibility of green ammonia trading via pipelines and shipping: Cases of Europe, North Africa, and South America., Journal of Cleaner Production, 427, 39212.
32. https://doi.org/10.1016/j.jclepro.2023.139212 Anuario-de-Estadisticas-del-Cobre-y-Otros-Minerales-2005-2024 , https://www.cochilco.cl/web/anuario-de-estadisticas-del-cobre-y-otros-minerales/ , accessed November 2025.

33. Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2018). Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework. *Ecological Indicators*, *88*, 250-262.
34. Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., ... & Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science advances*, *9*(37), eadh2458.
35. https://ecoinvent.org/database/, accessed August-November 2025
36. Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. *Energies*, *10*(7), 860. https://doi.org/10.3390/en10070860
37. Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. *JRC130796, Joint Research Center, Editor*.