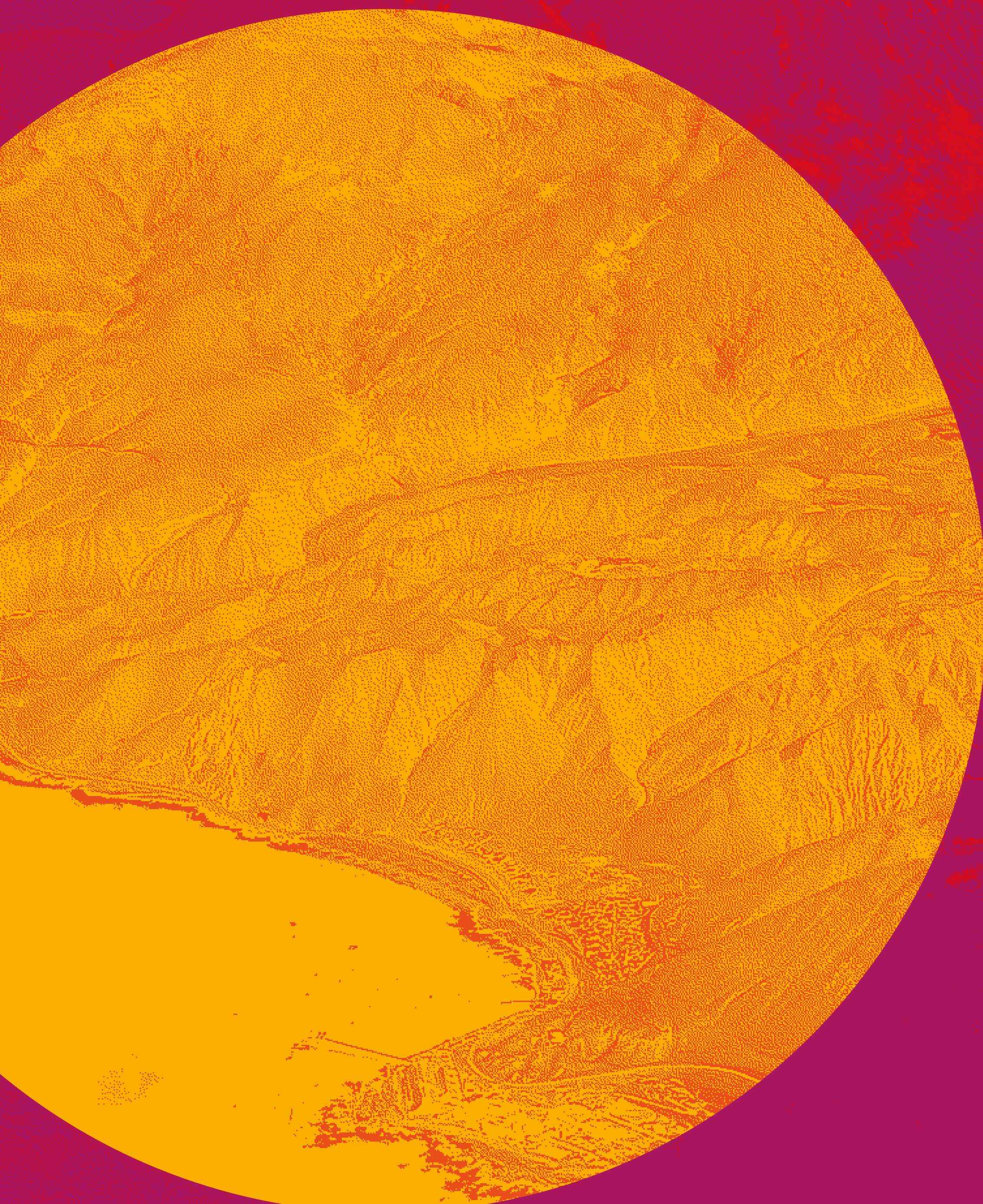
The Chilean Potential for **Exporting Renewable Energy**



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The Chilean Potential for **Exporting Renewable Energy**

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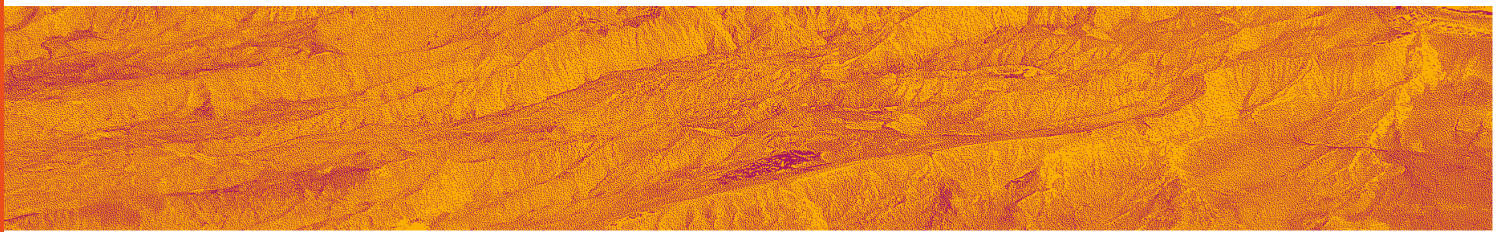


The Chilean Potential for Exporting Renewable Energy

Abstract

This document seeks to contribute to society and its decision-makers with the bestavailable scientific evidence on Chile's Renewable Energy (RE) Export Potential and the opportunities and challenges that such potential opens for Chile's commitment to carbon neutrality . It also aims to provide a useful input for the dialogues that the country will hold in the framework of COP26. A collaborative and interdisciplinary process was developed for this goal, involving 69 researchers and specialists. The work incorporates 299 references of scientific literature that support the different dimensions involved in the challenge of exporting renewable energy from Chile. It is confirmed that Chile has a considerable renewable energy potential that can be the basis for various exports. The different energy export options identified are: renewable electricity using electrical transmission grids; hydrogen and derivatives (synthetic fuels, fertilizers, other chemical products) through pipelines or maritime transport; local production or manufacturing of products and services fed with RE; and knowledge and R&D capabilities. We conclude that the whole process of renewable energy exports should be framed within the Chilean policy for climate change and the current local context. Moreover, such a process must be consistent with the social and environmental principles set out in Chile's NDCs, in the future Framework Law for Climate Change, in its Long-Term Climate Strategy, and in the mitigation and adaptation plans of the energy sector. For this purpose, recommendations were developed in the following areas: Art. 6 of the Paris Agreement, climate observatory, legitimacy and social licence, just climate action principle, energy literacy, new challenges for science and technology, partnerships, and improvements of the current legislation.

Keywords

Mitigation, COP26, Chile, sustainable development, Paris Agreement, renewable energy, green hydrogen, climate change, climate policy, export, sustainability.

1. Introduction

Chile and the world are facing unprecedented challenges as a result of climate change and the associated energy transformations, as affirmed by the Working Group I contribution to the IPCC's 6th Assessment Report on the physical understanding of recent climate change (IPCC, 2021). That is why COP 26, to be held in Glasgow in November 2021, has become especially relevant as a space for the generation of agreements that will enable rapid progress in this transformation process. In this context, the Chilean Ministries of Science and Energy have asked the Scientific Committee on Climate Change to analyse and synthesize the scientific evidence regarding the export of clean energy from Chile and to connect this analysis with aspects associated with accounting under the Paris Agreement (PA), including both the level of emission reduction efforts committed by Chile in its Nationally Determined Contribution (NDC) and the transfer of emission reduction certificates under Article 6. When a country exports clean energy via electricity grids or fuels such as green hydrogen, it must ensure the environmental integrity of these transactions by enforcing standards and robust rules to avoid double-counting, and by considering ecological and social concerns. The analysis also seeks to integrate a preliminary assessment of the region's energy integration challenge while taking into account the potential for renewable energy (RE) exports in Latin America to identify our region's role in this area in the world by analysing the possible dilemma between meeting national commitments (NDCs) versus exporting mitigation capacity to other countries.

The following subsections present relevant contextual elements that are discussed in greater depth in Chapters 3 and 4.

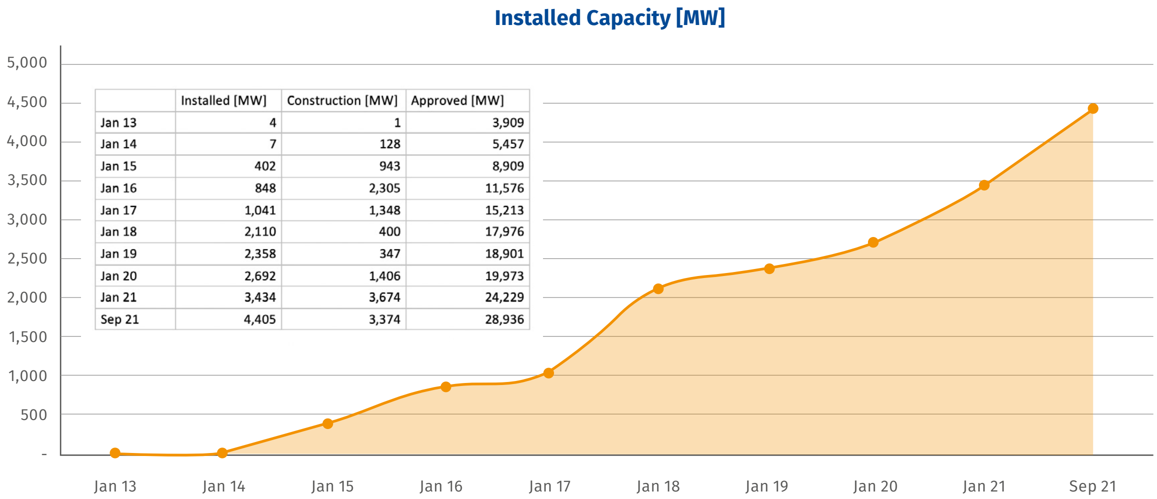
1.1. Chilean energy context and climate change

In the transformational context that the country is undergoing (social, political, institutional), environmental awareness, climate change, biodiversity protection, increasing use of natural resources, local pollution, social concerns, territorial impacts, and energy poverty have become particularly relevant affairs. For example, the first Framework Law on Climate Change (FLCC) is currently being debated in the National Congress and is expected to become a Law of the Republic before the end of the year 2021.[1] On the other hand, the plan for the retirement and/or reconversion of coal-fired power plant units was announced by the end of 2019 as a result of a voluntary agreement between the private sector and the government (Ministerio de Energía, Gobierno de Chile, 2021a). Recently, in July 2021, the retirement of more coal-fired plants by 2025 was added to this announcement, adding 1,000 MW to the previously agreed plan.[2] A specific law for the early phase-out of coal-fired generation plants by 2025 is also under discussion in the Senate.[3]

Despite the progress made, Chile remains highly dependent on fossil fuels, which account for 57% of its final energy consumption. In this context, RE has had an unprecedented development since 2015. Figure 1 exemplifies this evolution in terms of solar energy.

1 https://www.senado.cl/appsenado/templates/tramitacion/index.php?boletin_ini=13191-12
2 https://www.efe.com/efe/america/economia/chile-anuncia-el-retiro-anticipado-de-cuatro-centrales-carbon-para-2025/20000011-4580216
3 https://www.latercera.com/pulso/noticia/la-salida-del-carbon-de-la-matriz-electrica-chilena-se-acelera/22GKFYRWMFAEVNGXQBAUSLWA7Y/

Figure 1
Evolution of installed solar capacity in Chile since 2013
Source: Developed by the authors based on the monthly RE report, National Energy Commission.



	Installed [MW]	Construction [MW]	Approved [MW]
Jan 13	4	1	3,909
Jan 14	7	128	5,457
Jan 15	402	943	8,909
Jan 16	848	2,305	11,576
Jan 17	1,041	1,348	15,213
Jan 18	2,110	400	17,976
Jan 19	2,358	347	18,901
Jan 20	2,692	1,406	19,973
Jan 21	3,434	3,674	24,229
Sep 21	4,405	3,374	28,936

Furthermore, the first 110 MW concentrated solar power tower plant in Latin America came into operation in Chile in 2021. Renewable technologies now account for 53% (14,221 out of 26,737 MW) of the country's total installed capacity of electricity generation. Solar, wind, biomass, and mini-hydropower account for 28% (8,006 MW) of installed Capacity and have already exceeded 20% of the annual energy generation.[4] Although RE development has been impressive, it still represents a very small percentage of Chile's estimated potential of 2,375,000 MW (Ministerio de Energía, Gobierno de Chile, 2021b). This potential offers excellent options for RE to play a central role in the required energy transformation, but it needs to be addressed within ecosystem limits and under an energy justice concept. Also, an energy efficiency law has been enacted, which is expected to reduce energy intensity by 10% at a national level, in addition to producing significant monetary savings and reducing greenhouse gas (GHG) emissions.[5]

As evidenced in the actions mentioned above, Chile advanced significantly in the fight against climate change, following the adoption of the Kyoto Protocol, the presidency of COP 25, and the NDC update of last year. In fact, in April 2020, Chile was one of the first countries to officially submit an update of its NDC target to the UNFCCC (Ministerio del Medio Ambiente, Gobierno de Chile, 2020).[6] Consortiums like The Climate Action Tracker recognize that Chile has increased its climate ambition. In fact, the rating moved from "Highly Insufficient" to "Insufficient".[7] On the other hand, the "Insufficient" rating indicates that Chile's climate policies and commitments need substantial improvements to be consistent with the 1.5°C temperature limit goal.

1.2. Historical perspective

1.2.1. Trajectory

In the area of technological developments, Chile is usually perceived as a country with low innovation levels that has never developed heavy (railways, mining, forestry, machinery, among others) and technology-based industry. However, as we will show in this section, there is evidence that there have been actions and activities in the country that show the innovative use of solar resources. The available information reveals that Chile was a part of the global trajectory of industrial capitalism, which became translated into commerce of artifacts and production appropriate for the local level. Although industrialization models are currently questioned, it is convenient to review and weigh such a general assessment by different means (Kallis & Norgaard, 2010).

For instance, the Chilean industrial census of 1895 (SOFOFA, 1897) allows an appreciation for the growth of mining and other industrial projects. Led by the President of the Republic, José Manuel Balmaceda, industrialization was the visible face of the project that sought to consciously transform Chile into a modern country (Sagredo-Baeza, 2012).

4 http://energiaabierta.cl/visualizaciones/capacidad-instalada/
5 https://energia.gob.cl/ley-y-plan-de-eficiencia-energetica
6 Spanish version: https://mma.gob.cl/wp-content/uploads/2020/07/Espanol-21-julio.pdf; English version: https://mma.gob.cl/wp-content/uploads/2020/07/Ingles-21-julio.pdf
7 https://climateactiontracker.org/countries/chile/

At those transitional times (last quarter XIX c., first-quarter XX c.), Chile had a fruitful production of propositions of inventions able to use RE (Escobar Andrae & Arellano Escudero, 2019). Also, inside the Atacama Desert –former Bolivian territory– at least three solar desalination industrial projects were built and developed between 1872 and 1908 (Arellano Escudero, 2019). This early development of solar-energy harvesting had a significant role in producing nitrates and the exports of soil (salts and minerals) from Chile to the world. The narrative, which considers Chile an early laboratory for RE, can be strengthened thanks to Basalla's (1988) theoretical model about the evolution of the technology, explaining that the Chilean case is primarily a history of intermittent duration of the solar energy techniques.

The evidence shows that the nitrates industry has used solar energy intensively for harvesting magnesium and potassium since the 1940s, and later, for lithium in the 1970s through solar-pond technologies. All these processes are still working nowadays.

This environmental technology history constitutes a model of the historical trajectory of technology which has four eras: a) 1872-1908 for solar desalination continental waters, b) 1933-1950 for the beginning of solar ponds which are still functioning, c) the 1960s-1970s for the academic research headed by Julio Hirschmann Recht from Universidad Santa María de Valparaíso, and d) the XXI century in which RE are increasingly integrated to the national energy matrix.

Nevertheless, the lock-in of the techno-institutional complex of energy in Chile (Unruh, 2000, 2002; Unruh & Carrillo-Hermosilla, 2006) has considered multi-level users inconsistently: academic engineering research and development since the 1960s for domiciliary scale was discontinued for decades (Osses et al., 2019).

Nonetheless, the historical trajectory of RE in Chile demonstrates the persistence and endurance of researchers and institutions, reveals the unknown industrial heritage, and helps to cherish a local productive capacity to develop a RE techno-institutional complex in the foreseeable future.

1.2.2. Contemporary context

In the current context, *"we should not forget that not only does climate change represent a risk factor in accelerating, strengthening, amplifying and multiplying situations of uncertainty, conflict, violence and political crisis in the future, but proposed control and mitigation measures may also generate conditions of instability. Climate risks will be exacerbated by the local conditions of poverty and inequality, but they may be mitigated through adequate investments in institutional response and adaptation capacities, which implies structural transformations that strengthen the social fabric, the preparation of the population and governance conditions. On the contrary, the adoption of inappropriate policies may accelerate or even amplify uncertainty and conflict. The current social crisis in Chile is a stark reminder of these two types of enabling conditions that we need to consider"* (Palma Behnke et al., 2019).

In a certain way, the energy sector landscape in Chile could be another expression of the extreme social inequality represented by the extreme concentration of income in the country (De La Maza et al., 2021).

On the other hand, we believe that the fundamental reason behind the qualitative step forward in the level of ambition is the growing conviction among Chilean society, regardless of the political sector, about the need for stronger environmental protection. The growing environmental awareness is observed in that 88% of the citizens who responded to the 2018 National Environmental Survey (Ministerio del Medio Ambiente, Gobierno de Chile, 2018) believe that the main cause of climate change is human activity; 93% consider that this change is already occurring and 93% of the respondents state that climate change is very important or quite important for themselves, and 67% perceive it as important for Chileans. Indeed, it is a more empowered society that has managed to stop emblematic projects such as the Hidroaysén hydroelectric dam, Barrancones coal plant, and nuclear energy in 2010. The issues of air pollution in the capital city of Santiago since the 1980s, the largest and most severe drought in the last 700 years (Garreaud et al., 2015; Muñoz et al., 2020), and the country's vulnerability to climate change have also contributed to this awareness.

Research conducted on the predisposition of elites and citizens towards the energy transition shows that, although there is a favourable predisposition towards renewable energies in general, we are still far from knowledge, awareness, and proactive capacity adequate to the technological and cultural changes required for this transition to become a massive phenomenon (Parker et al., 2013; Parker, 2018, 2020). Thus, the acceptance of the RE projects may be controversial in some cases (Bronfman et al., 2012, 2015).

In the current context of the country's deepening democracy, any investment project promoted by the state and the private sector must take into account the society, its social and economic capital, and the history of the territories where it is to be developed, with the goal of ensuring that the investment contributes to social well-being, to the recovery and maintainance of ecosystems, and to environmental sustainability, rather than becoming a factor of conflict or conflict resolution.

1.3. Article 6 of the Paris Agreement and the challenges for the energy transition in Chile

Rapid and large-scale emission reductions are needed to cope with current and future climate impacts (IPCC, 2021). Strong political will, robust policies, and enabling instruments should shorten the mitigation gap to control the 1.5 °C increase before 2050. To this means, Article 6 of the PA[8] was included to help the Parties achieve their targets cost-effectively, either bilaterally or through multiparty arrangements that would derive into different cooperation options among countries. Article 6 established three key elements of the international carbon markets: two instruments, the cooperative approaches (Art. 6.2-6.3), and the sustainable development mechanism (Art. 6.4-6.7); different types of tradable units such as International Transfers of Mitigation Outcomes (ITMOs) or Emission Reduction Credits; and finally, the governance structure, centralized under COP or decentralized under bilateral-multilateral agreements. More specifically, the following instruments conform to the backbone of this article (Gao et al., 2019):

- Article 6.2: opens the possibility for ITMOs, for compliance with NDCs or other purposes, under contractual rules to be defined by the countries but following agreed, multilateral guidelines. It is more decentralized and dependent on bilateral or multilateral arrangements to be defined by the parties.
- Article 6.4: establishes a centralized mechanism operated and supervised by the United Nations, similar to the Clean Development Mechanism (CDM) under the Kyoto Protocol, through which projects or activities may be developed to generate reductions, which would be used to meet the NDCs or could be transferred for other purposes of the acquiring party.
- Article 6.8: the so-called "non-market mechanism", which promotes cooperation options to mitigate emissions without a transfer associated to the mitigation asset, i.e., emissions are reduced, but emissions are not transferred, nor a price is given to the asset (the ton of CO_2eq).

On the other hand, Chile's NDC, which reckons the mitigation potential that Article 6 could bring for its achievement, commits to a GHG emission budget not exceeding 1,100 MtCO_2eq between 2020 and 2030, with GHG emissions maximum (peak) by 2025, and a maximum GHG emissions level of 95 MtCO_2eq by 2030, and to a reduction of at least 25% of total black carbon emissions by 2030 compared to 2016. Emission reduction targets cannot be discounted by other mechanisms. This means that any transfers from Article 6 would not count towards Chile's NDC compliance: a corresponding adjustment procedure would be required to ensure the country is not double-counting its mitigation efforts. Additionally, as mentioned before, Chile is currently discussing the first FLCC that includes the net-zero commitment by 2050 and makes it legally binding. This law includes provisions for a baseline-&-credit system (Art. 14) wherein the authority sets an emissions limit to regulated entities (ranging from individual sources, groups of sources, or sectors) which could reduce their emissions below their baseline or implement emission-reduction projects that meet certain standards to earn credits. These reductions (or absorptions) need to demonstrate that they are: *additional, measurable, verifiable, permanent*, have environmental and social benefits, and comply with the NDC and the sustainable development goals. These credits could then be sold to other regulated entities to use for compliance. In the case of short-lived climate forcers (SCLF) that are local pollutants, certificates from emission reduction or absorption projects need to be performed in the area declared as saturated or latent. In addition, Article 29 regulates a system of voluntary certificates of GHG or SLCF reductions for the public and private sectors.

As per Art. 6, the authority will regulate emission reduction and removals certificates, in line with the Paris Agreement rulebook in this respect (Art. 15 of the FLCC). A dedicated registry would track the projects and the transfers. Therefore, according to the identified complexities of mechanisms of Art. 6 for the local context, an exporting's strategy of RE whose mitigation outcomes wish to be recognized as tradable certificates (ITMOs), creates a context of uncertainty regarding its structure and relation between economic benefits, capacity building, and forms of allocation of reduction in emissions through the time as well as the trade-off between exporters and importers accounting. Though challenging, this uncertainty can be reduced by exploring robust accounting methodologies that can reconcile the exporting of RE as ITMOs, without jeopardizing the committed carbon budget, and ultimately, the NDC.

1.4. Objectives and scope

This document seeks to contribute to society and its decision-makers with the best-available scientific evidence on Chile's Renewable Energy Export Potential and the opportunities and challenges that such potential opens for Chile's carbon neutrality commitment. It also aims to provide helpful input for the dialogues that the country will hold in the framework of COP26. The content and support of the document seek to comply with high standards of scientific rigor. It is beyond the scope of the document to generate a roadmap on the subject.

In the context of the scope of this work, it is essential to state that energy transitions involve technological and infrastructural changes in the energy sector, and inherently imply political processes that can transform social and cultural relations and

8 English version: https://unfccc.int/sites/default/files/english_paris_agreement.pdf; Spanish version: https://unfccc.int/sites/default/files/spanish_paris_agreement.pdf.

structures. This process can also be a possibility to move towards more democratic and fairer energy development models, but it can also reflect and reinforce existing power relations against these objectives. As part of the scope of this work, whose main focus is energy exports, it is necessary to incorporate in addition to the economic efficiency standards (allocative, productive, and dynamic efficiency), the dimensions linked to sustainable development goals and climate justice, considering the implications of justice and equity, which are part of Chile's NDC commitment to a social pillar of just transition and sustainable development.

Furthermore, the analysis of Chile's potential to take advantage of renewable energies includes the governance of the socio-ecological and innovation systems and processes that will allow the production of these energies in the country and eventual exporting. We understand governance as the way in which societies make decisions, i.e., the process that leads to collective action in pursuit of common goals (Ansell & Torfing, 2016; Sapiains et al., 2021).

1.5. Structure

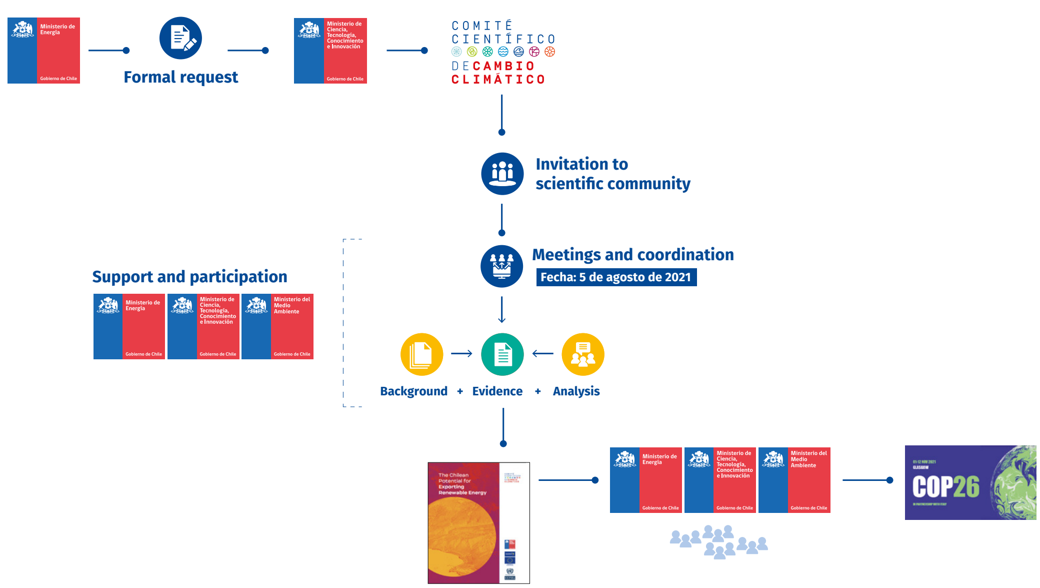
The document is organized into four thematic sections. Based on the background and context presented in the introduction, section 2 summarizes the participatory process, and the thematic dimensions addressed. Sections 3 and 4 present the background analysis in each of the relevant dimensions, seeking to follow the value-added chain of the export options analysed and cross-cutting issues. Finally, section 5 corresponds to the stage of synthesis and recommendations based on the analyses presented.

2. Methodological approach

2.1. Collaborative process

In order to develop the present investigation, the scientific community was invited to join the collaborative process that sought to gather and synthesize the scientific evidence available in this area. **Figure 2** summarizes the main stages of the construction process of this document. The process began with a formal request from the Ministry of Energy to the Ministry of Science, Technology, Knowledge, and Innovation. Next, the Scientific Committee issued a call where nearly 700 researchers were invited.

Figure 2
Collaborative process
Source: Developed by the authors.



In the plenary coordination meeting, several dimensions were identified and highlighted as relevant to the main topic (see next section). Seven thematic groups, one for each dimension, were organized and coordinated voluntarily by researchers who accepted to participate in the process. These groups generated the content and evidence that constitute the different sections of the document.

The document and its background were handed openly to all participants in order to maximize their contributions, and at the same time, to inform them about the progress of the process. Although the document seeks to portray a shared analysis, the final version documents the evidence of conflicting views that arise from the analyses that were carried out.

2.2. Relevant dimensions

Based on the first outcomes of the collaborative process, the seven dimensions that were identified as relevant and that are studied in this report are: social, environmental, technological, economic, institutional, building of interactive and dynamic capacities, and political. In order to organize the content, first, we identify and define different export options. These export options are then analysed, considering the seven dimensions that were previously mentioned. Cross-cutting issues that are relevant to all export options are included in a separate section. Such analysis is the basic input for the synthesis and recommendations section. An analysis of the uncertainties is also carried out, so that the recommendations allow the identified vulnerabilities to be recognized in order to promote robust solutions.

Additionally, it was agreed that the production and export processes could not be analysed independently, as they are deeply related, e.g., appropriate technologies for the required scale of production, and regulatory standards to be met. Production needs technological capabilities, which can be basic capabilities to operate processes, where innovation can be passive and incremental; sufficient capabilities to develop improvements, such as adaptation of infrastructures to local conditions and preventive maintenance; or innovative capabilities, which allow the creation of new technologies and substantive changes in process design (Viotti, 2002).

3. Export options

This section presents the central elements of analysis of this study. First, it defines what is to be considered an export in order to delimit and organize the information to be analysed. Subsequently, Chile's renewable-energy production potential is characterized, followed by an analysis of the different renewable-energy export options: electricity interconnections, green hydrogen, hydrogen derivatives, and other value-added products, and finally, the export of RE embedded in products and services produced through local productive development or attracting international industry. The evidence that refers to the cross-cutting aspects of the above-mentioned export options is incorporated in the final section of this chapter.

3.1. Definition of renewable energies exports from Chile

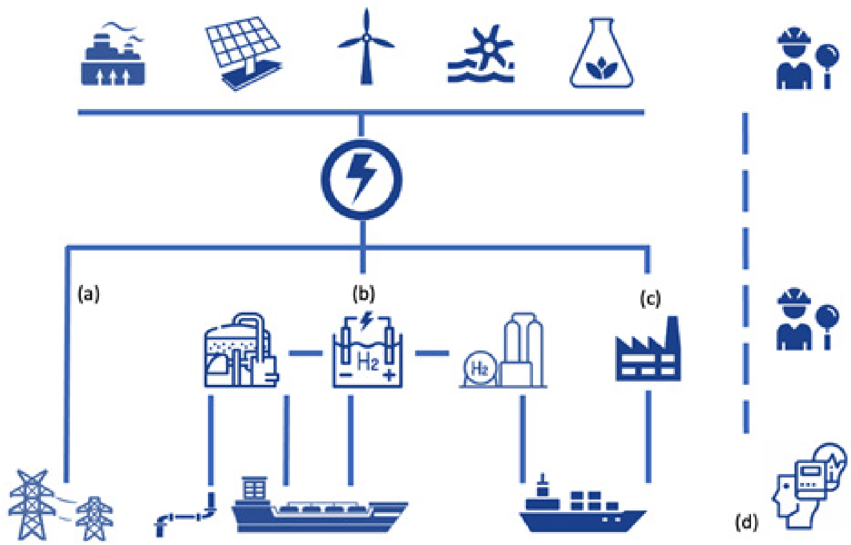
Although it may seem obvious, it is necessary to define what is meant by an export of RE from Chile. Exports of goods and services consist of transactions in goods and services (sales, barter, and gifts) from residents to non-residents.[9] Exports of goods occur when the economic ownership of goods changes between residents and non-residents. This applies irrespective of corresponding physical movements of goods across frontiers.

On the other hand, according to the European Environmental Agency, RE sources are defined as renewable non-fossil energy sources: wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogases. The basic and more developed process required for RE sources (mainly geothermal, solar, wind, hydro, biomass) is the conversion to electrical energy, allowing its subsequent use for any alternative use.

Based on the definition of export and RE, it is feasible to identify four primary forms of renewable-energy exports from Chile. Figure 3 summarizes the four options.

9 European System of Accounts (ESA 2010).

Figure 3
Export options
Source: Developed by the authors.



a. Direct export of electricity from renewable sources using electrical transmission networks.
b. Direct export of hydrogen and by-products (synthetic fuels, fertilizers, other chemical products) through maritime transport or pipelines.
c. Production or manufacturing by Chilean or international companies of products and services locally (an energy-intensive industry with low carbon footprint requirements) with RE and then export their products to the rest of the world through maritime transport.
d. Export of knowledge and research and development (R&D) capabilities, resulting from the activities and developments related to the options described in the previous points.

Each of these export options is discussed in depth in Section 3.3-3.7.

3.2. Renewable energy potential

Based on different studies and statistics developed during the last few years, it is possible to characterize Chile's RE potential according to the following criteria:

- Technically and economically feasible volume expressed as capacity.
- Quality of the resource in terms of performance of existing generation plants (plant factors, variability).
- Cost performance based on supply bidding results and market competitiveness.
- Future resource projection under climate change scenarios.

It is worth mentioning the importance of the role of the State in producing and keeping updated the relevant information associated with the potential of renewable energies in the aforementioned dimensions. This is especially important from the perspective of the principle of sovereignty of the associated resources, a topic that will be discussed in the following sections.

3.2.1. Resource Capacity

To quantify the renewable-energy potential, recently, the Information Management Unit of the Sustainable Energy Division of the Ministry of Energy developed a methodology for identifying renewable potentials through the combined use of geospatial information and the application of criteria by selection tools in geographic information software (ArcGIS 10.5.1).

Figures 4 and 5, and Table 1 summarize Chile's RE potential for electricity generation through the most recent analysis conducted by the Ministry of Energy in the Long-Term Energy Planning process (PELP),[10] carried out by the Energy Planning and New Technologies Unit of the Energy and Environmental Policy and Studies Division of the Ministry of Energy. This translates into the potential by type of technology summarized in Table 1.

10 pelp.minenergia.cl

Figure 4

RE potential for electricity generation

Source: Ministerio de Energía, Gobierno de Chile (2021a)

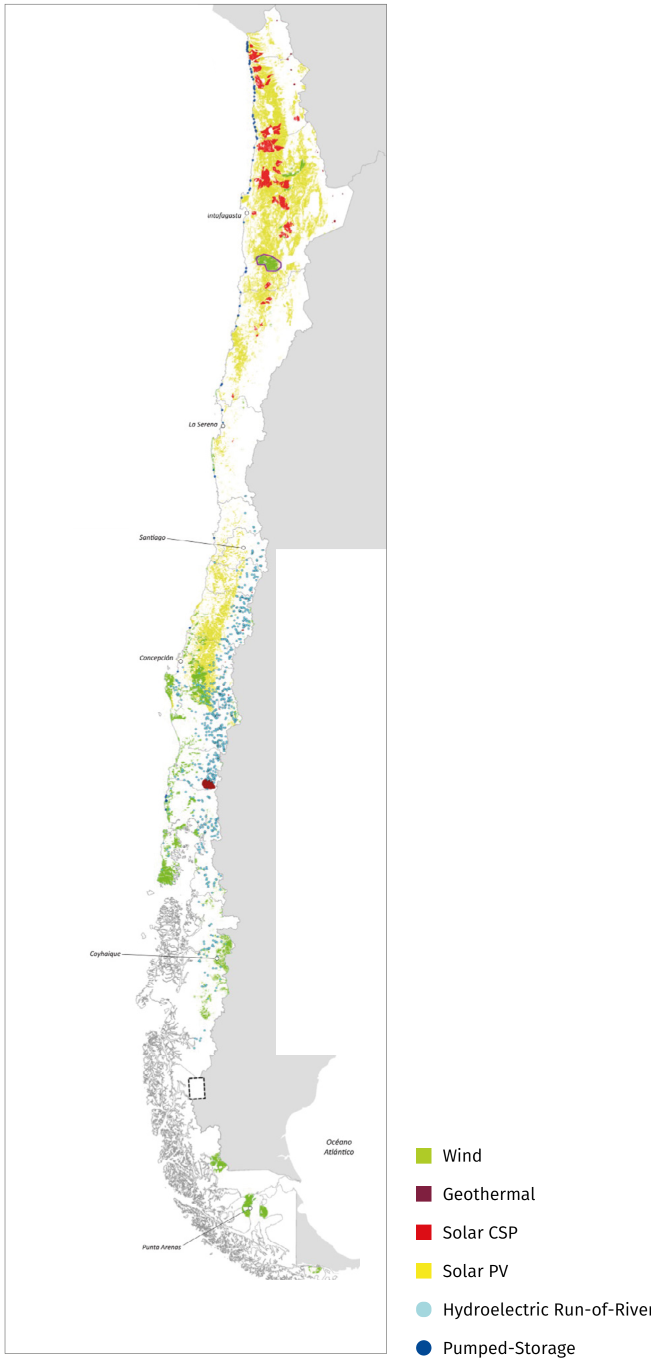


Table 1

RE potential for electricity generation by zone and type of RE

Source: Ministerio de Energía, Gobierno de Chile (2021b)

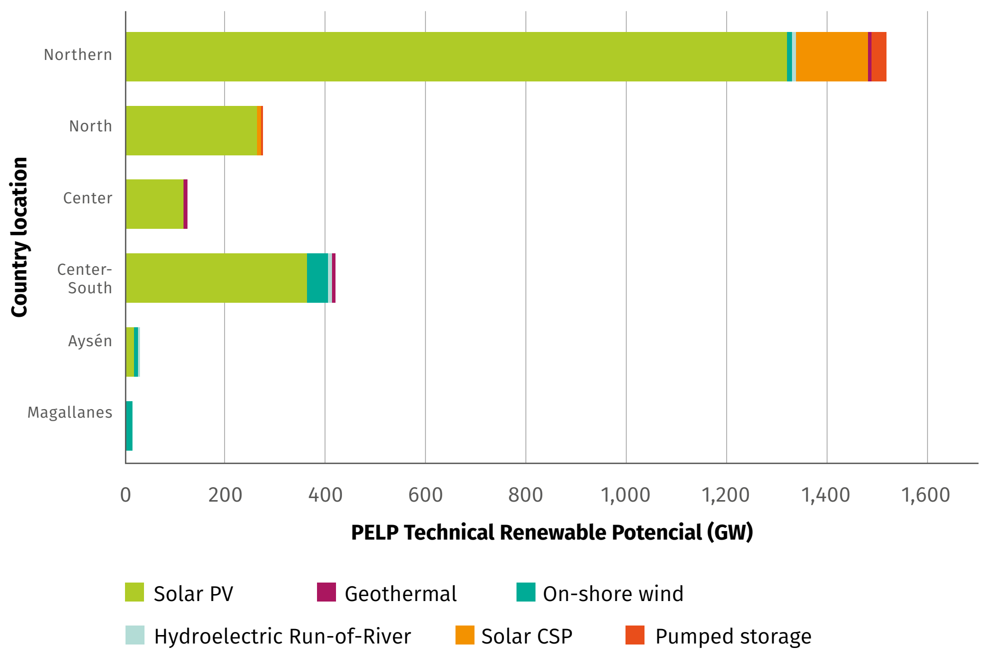
Technology	Country location						PELP Technical Potential (GW) Total
	Northern	North	Central	Central-South	Aysén	Magallanes	
On-shore wind	14	2	0	42	11	12	81

Geothermal	3	0	0	1	0	0	4
Solar CSP	145	7	0	0	0	0	152
Solar PV	1,326	264	118	363	13	2	2,086
Hydroelectric Run-of-River	0	0	1	8	1	0	10
Pumped storage	34	4	0	4	0	0	42
Total	**1,521**	**276**	**120**	**419**	**25**	**14**	**2,375**

Figure 5

RE potential for electricity generation by zone and type of RE

Source: Ministerio de Energía, Gobierno de Chile (2021b)



This potential does not include small-scale distributed generation or decentralized energy solutions (Ministerio de Energía, Gobierno de Chile, 2021b), from residential and small commercial/productive sectors, which can enable, together with energy efficiency measures, better conditions for utility-scale plants to export renewable electricity or produce hydrogen and its derivatives. In fact, small-scale solar photovoltaic (PV) systems can supply a significant part of the electricity demand within a country, releasing transmission network capacity at given times and reducing the need for energy from new utility-scale power plants (Child et al., 2019), which can be used for exporting. Although the current installed capacity of small-scale distributed PV generation in Chile (up to 300 kW) is only about 56 MW, it is expected to grow significantly in the next 20 years, reaching between 3,500 and 6,300 MW in 2040, depending on the scenario (E2BIZ, 2021). In some scenarios, distributed generation can even represent about 40% of the new installed capacity until 2040 (Lobos et al., 2021), and small-scale distributed PV generation can supply about 40% of the total electricity demand from the power sector by 2050 (Osorio-Aravena et al., 2021). In the case of PV solar energy, the development of large generating plants helps to reduce costs in low-scale applications. Panels, structures, inverters, and control systems can be the same, opening great options for the competitive development of productive decentralized energy solutions.[11]

11 See, for example, www.ayllusolar.cl.

It should also be noted that in the case of having more distributed generation than demand at given times, the corresponding export potential should be calculated considering the need of ensuring distribution network integrity (operating within technical limits) (Petrou et al., 2021; Gutierrez-Lagos et al., 2021).

The identification of areas that meet favourable conditions for the installation of RE projects is based on the selection and superimposition of geo-referenced factors that require restriction thresholds in order to establish in which locations it is desirable to develop energy projects, to the extent that they comply with the proposed limits. Table 2 summarizes the thresholds (constraints) and criteria used for the most recent PELP study.

Table 2
Factors and thresholds for the evaluation of RE potential
Source: Ministerio de Energía, Gobierno de Chile (2021b)

	Onshore Wind	Solar Photovoltaic	Concentrated Solar Power CSP	Hydroelectric Run-of-River	Geothermal
Technical factors					
Plant factor	< 30%	< 21%	-	< 50%	No restr.
Direct Normal Irradiation	-	-	No restr.	-	-
Slope	> 15°	> 10° north orientation and > 4° others	> 7°	-	-
Altitude	> 3,000 MASL	> 4,000 MASL	-	-	-
Percentage of cloudiness	-	-	< 20%	-	-
Percentage of hours with wind speed > 15 m/s at 5.5 m height	-	-	< 0.5%	-	-
Project areas OPC	ZEP	ZEP	ZEP	-	-
Distributor Tender Project Areas	-	-	ZEP	-	-
National Assets for Energy Purposes	-	-	ZEP	-	-
Taltal Reserve Area	-	-	ZEP	-	-
Wind Power Potential 2021	-	-	ZEP	-	-
Environmental factors					
SNASPE	ZEP	ZEP	ZEP	ZEP	-
Ramsar sites	ZEP	ZEP	ZEP	ZEP	-
Salt flats	ZC300	ZC300	ZC300	-	-
Water bodies inventory	ZC300	ZC300	ZC300	-	-
Glacier inventory	ZC300	ZC300	ZC300	-	-
Active volcanoes	ZEP	ZEP	ZEP	-	-
Territorial factors					

Table 2 (Continuation)

Territorial planning instruments boundaries (urban boundaries and consolidated urban areas)	ZC1000	ZC1000	ZC1000	-	-

Inventory of anthropized water bodies	ZC300	ZC300	ZC300	-	-
Rivers/hydrographic network inventory	ZC300	ZC300	ZC300	-	-
Road network	ZC60	ZC60	ZC60	-	-
Coastal line	ZC100	ZC100	ZC100	-	-
Land use capacity classes	-	-	ZEP	-	-
Mine tailings	ZEP	ZEP	ZEP	-	-
Minimum continuous area (ha) or minimum power (MW)	112 ha Z1; 168 ha Z2	12 ha (equiv. to 3 MW)	700 ha (equiv. to 100 MW)	min. 3 MW	-

OPC: Projects in operation, in testing or in construction.
ZEP: Exclusion zone due to presence.
ZC300: Nearby areas up to 300 m.
ZC1000: Nearby areas up to 1000 m.
ZC60: Nearby areas up to 60 m.
ZC100: Nearby areas up to 100 m.
Z1: between Arica and Coquimbo.
Z2: between Valparaíso and Magallanes (equiv. to 5.6 MW).

Chile has great renewable resource potential, with a clear predominance of solar energy, followed by wind and geothermal energy. This potential can be compared with the country's total electricity generation capacity of around 27 GW, of which about 14 GW are from renewable generation sources (approximately 1% of the potential mentioned above).

The available ocean energy potential, estimated at an additional 160 GW (Cruz et al., 2009), is not included in the Ministry's study. However, the potential indicated for hydraulic pumping, does not correspond to a primary energy source, strictly speaking, so it should be considered as generation capacity at the service of energy storage systems for the energy provided by the rest of the energy sources. With these considerations, the estimated potential would be around 2,493 GW, which does not change the conclusions presented.

Nevertheless, it is essential to highlight that the study of applicable thresholds in the technical, environmental and territorial dimensions presents significant challenges to include additional restrictions associated with impacts on biodiversity, specific ecosystems, sociocultural aspects, and climate change projections. Some of these issues are crucial to identifying territorial limits (ecosystemic and sociocultural) of the potential that cannot be visualized and that can play a key role in implementing an export strategy. For example, large marine mammals and birds play a key role in the biological transport of materials between land and ocean in the Magallanes region (Rozzi et al., 2021). Bats and migratory birds could be affected by a massive development of wind energy fields, even in off-shore plants, due to three types of risks: collisions, electrocution, and barotrauma (SAG, Gobierno de Chile, 2015). Migratory birds are especially affected because of the magnitude of their populations arriving during the austral summer, and because the funnel-shape of the South American continent forces all of the migratory species from the northern hemisphere and tropical latitudes to go through common migratory routes that end at the Magallanes region, at the southernmost tip of America (Rozzi & Jiménez, 2014). Additionally, some impacts are common to all types of projects, such as habitat loss, the introduction of invasive species, and habitat fragmentation through power line corridors. Power transmission lines could also generate electromagnetic impacts; however, this has not been sufficiently studied to date (SAG, Gobierno de Chile, 2015). Moreover, under current regulation mechanisms, infrastructure projects have been identified among the largest threats to the ecosystem in this area (Rozzi et al., 2021).

Although the environmental impact evaluation in Chile considers the synergic effect of wind power fields, planning tools for wind energy projects such as the Soaring Bird Sensitivity Mapping Tool[12] are not integrated into the analyses, and there is not enough historical data in order to understand the different migratory dynamics of bird species in the south. To achieve effective planning, there is a need to identify species, ecosystems and areas of particular sensitivity, through the mapping of potentially unsuitable sites for wind energy development based on nature conservation principles, e.g., avoiding impacts on peatlands, forests, coastal zones and migratory routes. This requires increasing information available, especially for offshore wind plants. The impact of associated infrastructure, such as power lines, roads, maintenance activities, etc., should also be taken into account and assessed together. Bladeless windmills are an alternative for wind power generation, minimizing the impact of these structures on birds (migratory and resident) and bat populations, However, there are concerns related to its design and efficiency of power production, and it may take some time to gain popularity within the industry (May et al., 2015).

It is also relevant to consider that RE projects introduce elements that affect local coexistence and culture. These projects may occupy territories inhabited by rural or indigenous populations accustomed to practices, landscapes, and habitats, so their

12 https://maps.birdlife.org/MSBtool/.

introduction may modify their technical and daily routines, generating resistance to them, as has happened in the cases of wind turbines in Chiloé (Baigorrotegui & Parker, 2018). The situation described above suggests that it is necessary to take up the local community's previous learning and encourage participatory renewable projects.

Another example is the release of GHGs from hydroelectric reservoirs due to the decomposition process of the organic matter that is flooded beneath the waterline. While this issue has received broad attention for tropical reservoirs, the contribution of temperate and boreal systems may have been overlooked, especially in a global warming scenario. With the exception of Adams et al. (2000), to the best of our knowledge, no studies have measured GHG diffusion in Chilean reservoirs. Efforts to standardize measurements and calculations have been underway (IHA, 2010; Kumar et al., 2012), and a recent review still reports a considerable lack of adequate data (Lu et al., 2020). DelSontro et al. (2010) suggests that GHG budgets should give further consideration to temperate and boreal reservoirs and Mar (2009) recommends the development of sampling strategies to collect country-specific data in Chile.

In addition to these uncertainties, it should be noted that the estimated potentials cited above do not consider the possible effects of future climate scenarios.

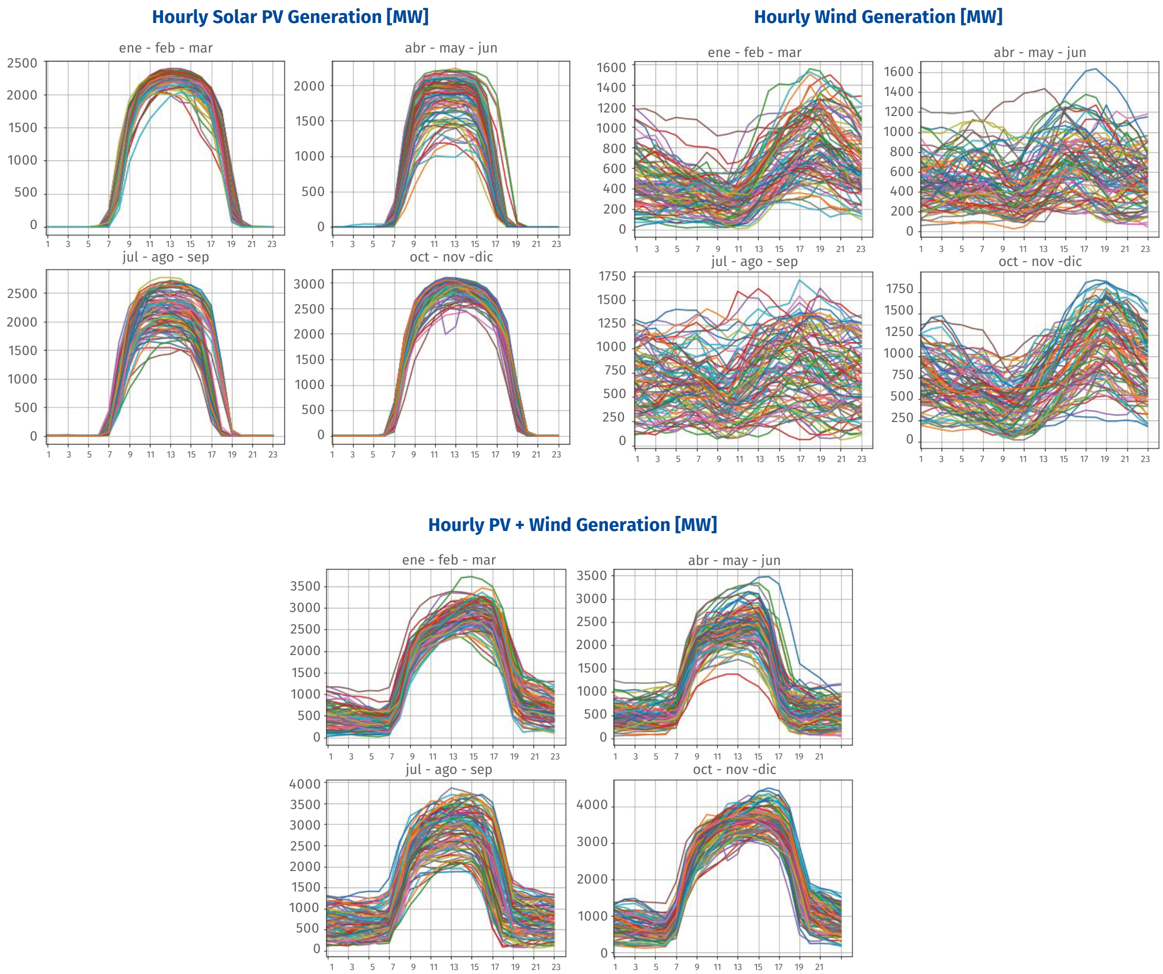
Finally, it is worth mentioning that the export scenarios outlined in the National Green Hydrogen Strategy involve a combined use of around 300 GW of solar and wind energy (Ministerio de Energía, Gobierno de Chile, 2020). This amount would not exceed 12% of the estimated potential. Still, as already mentioned, implementing solutions in a territory requires compliance with environmental regulations and knowledge of the possible ecosystemic and sociocultural impacts, resulting in additional limits that should be respected.

3.2.2. Renewable resource quality

The thresholds required in the potential assessment already show the quality of the renewable resource in Chile. For example, plant factors of over 21% and 30% are considered for solar photovoltaic and wind energy, respectively. The average plant factor of the solar resource in Germany does not exceed 7%; in other words, a solar plant in Chile can produce more than three times the energy it would produce if it were located in Germany (Jimenez-Estevez et al., 2015). Recent studies have enabled us to characterize and understand our country's solar resources in greater detail. Also, based on the full year 2020 operating statistics from the National Electricity Coordinator,[13] Figure 6 show the solar, wind, and combined generation observed daily in Chile for the year 2020.

13 https://www.coordinador.cl/

Figure 6
Daily performance of solar and wind energy in 2020 [MW]
Source: Osses (2021).



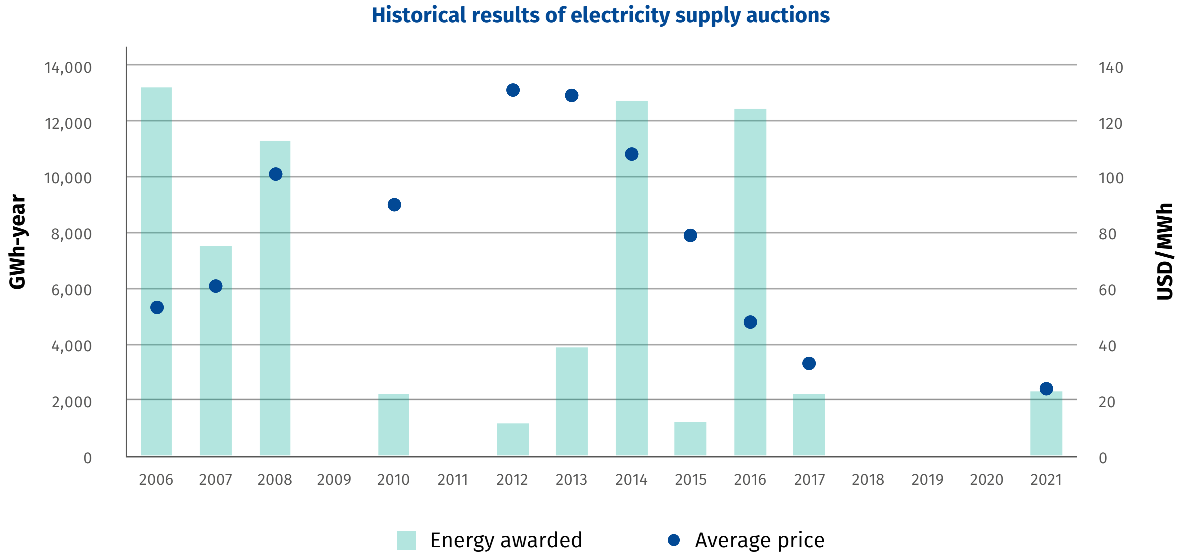
There is a systematic contribution of sunlight daily and with low variability in the spring and summer months. The annual solar plant factor is estimated at 29,9%. Likewise, as expected, wind energy presents a more significant variability but with marked profiles for the summer and spring months. In this case, the annual plant factor is estimated at 33,4%. Finally, it is notable that the combined solar/wind contribution reached around 4,000 MW by the end of 2020, which shows a complementarity between the two resources.

3.2.3. Costs

The costs of energy production from renewable solar and wind energy have dropped over the last decade. For example, the Levelized Cost of Electricity (LCOE) for photovoltaic has decreased by 85% and onshore wind by 56% (IRENA, 2021). Costs to generate renewable electricity depend on the technology and its respective level of available energy resource in a specific location. In the case of Chile, for electricity exports to the South American region, solar PV technology has been identified as a key option (Jimenez-Estevez et al., 2015). For instance, in the Atacama Desert, the monthly averages of daily solar radiation indices are between 5 and 12 kWh/m^2 from winter to summer for Global Horizontal Irradiance (GHI) (Escobar et al., 2014; Vyhmeister et al., 2017). Further, in the Atacama Desert, the annual average for daily irradiation for GHI is over 7.5 kWh/m^2 and 9 kWh/m^2 for Direct Normal Irradiance (DNI). Therefore, these irradiation values allow the development of competitive solar projects. The LCOE for solar PV fixed tilted and single-axis across the continental Chilean territory, assuming a weighted average cost of capital (WACC) of 7%, is expected to fall from a range of 20.2–42.6 €/MWh and 19.1–44.1 €/MWh to 7.5–16.1 €/MWh and 7.3–16.7 €/MWh by 2050, respectively (Osorio-Aravena et al., 2021). In both PV arrays, the lower costs take place in the North of the country. In any case, sensitivity analysis shows that apart from location, WACC is the most important input parameter in calculating PV LCOE, where increasing nominal WACC from 2 to 10% will double the LCOE (Vartiainen et al., 2020). Similar trends are observed in the case of wind energy.

Likewise, from the supply tenders in Chile, with a significant presence of renewable energies from 2015 onwards, the increase in competitiveness of this type of resource can be seen. **Figure 7** summarizes this trend. It is worth noting that 100% of the energy awarded has gone to bids from renewable resources (wind and solar power) in the last two tenders. Although these trends are supported by the analysis of the LCOE evolution of different international institutions,[14] the competitiveness values achieved in tenders at the national level stand out.

Figure 7
Historical results of electricity supply auctions
Source: Ministerio de Energía, Gobierno de Chile.



3.2.4. Environmental constraints

Concerning the environmental impact of renewable electricity generation, the IPCC document for Energy Systems (Edenhofer et al. 2014) presents ranges of global warming potential (GWP), estimated by life cycle assessment (LCA) methodology of 18–180 gCO_2eq/kWh for PV; 9–63 gCO_2eq/kWh for CSP, and 7–56 gCO_2eq/kWh for wind power, where the upper part of the range is associated with smaller turbines (< 100 kW). Regarding geothermal power, the document reported 6–79 gCO_2eq/kWh, and 2–23 gCO_2eq/kWh for ocean energy. Finally, for biomass (dedicated and crop residues), the values are between 120 to 400 gCO_2eq/kWh.

Higher values of GWP and acidification potential (AP) reflect that some RE technologies are currently produced using a certain amount of non-renewable, hydrocarbon-based energy. As the level of RE used in the manufacture of these technologies increases, their GWP and AP values will decrease.

An LCA of renewable electricity generation was carried out in Chile by (Gaete-Morales et al., 2018). Results of the GWP and AP for different technologies are summarized in **Table 3**. These results indicate that renewable electricity generation from hydro processes (reservoir and run-of river) presents the lowest AP and GWP potential, followed by wind power and PV. However, we must note that methane emissions for hydropower reservoirs were assumed to be 14 mg CH_4/kWh. This estimation was taken from the Ecoinvent database[15] for the Alpine-region reservoirs (considering this region has similar geographic and climate conditions to some regions in Chile). Biomass has the highest impact of all technologies assessed in terms of AP.

14 Webpages from: IRENA, NREL.
15 https://ecoinvent.org/the-ecoinvent-database/.

Table 3
GWP and AP for renewable electricity generation in Chile
Source: Developed by the authors with data from Gaete-Morales et al. (2018)

	GWP	AP
Unit	g CO_2 eq	mg SO_2 eq
Biogas	36	340
Biomass (heat and power)	50	776
Photo-voltaic	40	254
Wind (onshore)	8	33
Hydro (reservoir)	3	8
Hydro (run-of river)	2	6

Source: Gaete-Morales et al. (2018).

In addition to these environmental impacts, other indicators are helpful to understand the extent to which natural habitats in Chile have already been compromised. Marquet et al. (2021) made a first evaluation of the state of planetary boundaries in Chile. The planetary boundaries (Rockström et al., 2009) refer to:

- Climate change.
- Change in biosphere integrity (biodiversity loss and species extinction).
- Stratospheric ozone depletion.
- Ocean acidification.
- Biogeochemical flows (phosphorus and nitrogen cycles).
- Land-system change (for example, deforestation).
- Freshwater use.

These indicators regulate the stability and resilience of the earth system, and their level of disturbance by human activities should be limited in order to stay safe operating space.

The study in Marquet et al. (2021) found that eight boundaries are breached in Chile, in the following decreasing order: chemical pollution, fisheries, phosphorus use, loss in biodiversity, climate change, nitrogen use, use of fresh water from the northern to central Chile, air pollution. Only three of the boundaries analysed are below the limit: depletion of stratospheric ozone, the use of fresh water in Southern to Austral Chile, and the change in land use. We note that renewable energy development might affect three of the nine planetary boundaries: freshwater withdrawals, land conversion, and biodiversity loss at a domestic level. Other boundaries might be affected at the international level if the whole production process is considered –e.g., the manufacture of imported equipment required for RE plants.

3.2.5. Climate Scenarios – Vulnerability – Macrozones

Climate change affects every region of the world (IPCC 2021). In the case of Chile, the primary observed trend is a notorious decrease in precipitation in the central-southern region of the country (Boisier et al., 2018) (**Figure 8**), which has already been attributed, in part, to anthropogenic climate change (Boisier et al., 2016). In terms of temperatures, trends have spatial inhomogeneities. Most of the inlands and Andes show positive trends, with more significant trends at higher elevations and coastal regions showing either no trend or even cooling trends, that are partially driven by decadal oceanic variability (Burger et al., 2018; Vuille et al., 2015) (**Figure 9**).

Since the Atacama Desert and the Magallanes region have been classified as regions with a significant renewable-energy potential, it is crucial to present climate change projections for the near-term (defined as the period 2020-2040 in the IPCC WG1 AR6 report) in these regions.

Figure 8

CMIP6 projections of total precipitation change (%) for the mid-term (2041-2060) relative to 1995-2014 on the SSP5-8.5 scenario

Source: Interactive Atlas, IPCC WG1, 2021.

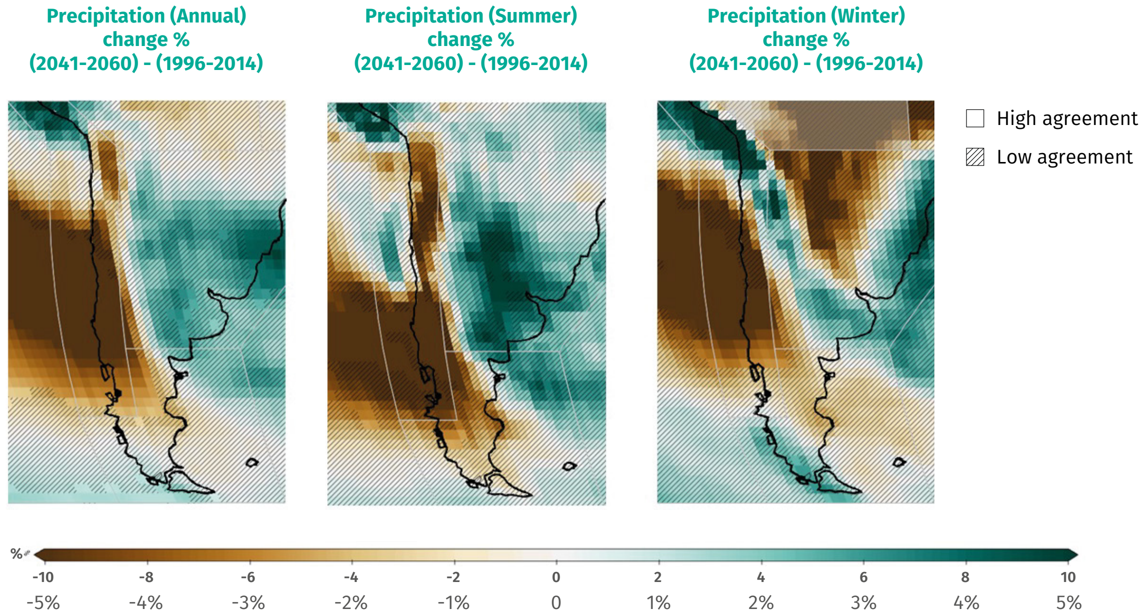
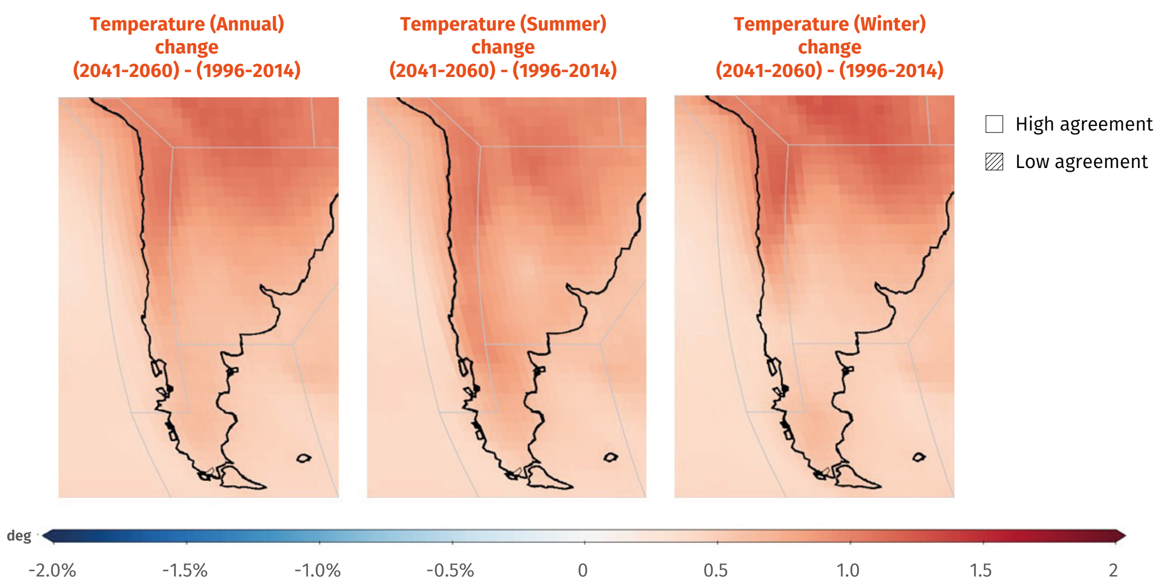


Figure 9

CMIP6 projections of mean temperature change (°C) for the near term (2021-2040) relative to 1995-2014 on the SSP5-8.5 scenario

Source: Interactive Atlas, IPCC WG1, 2021.



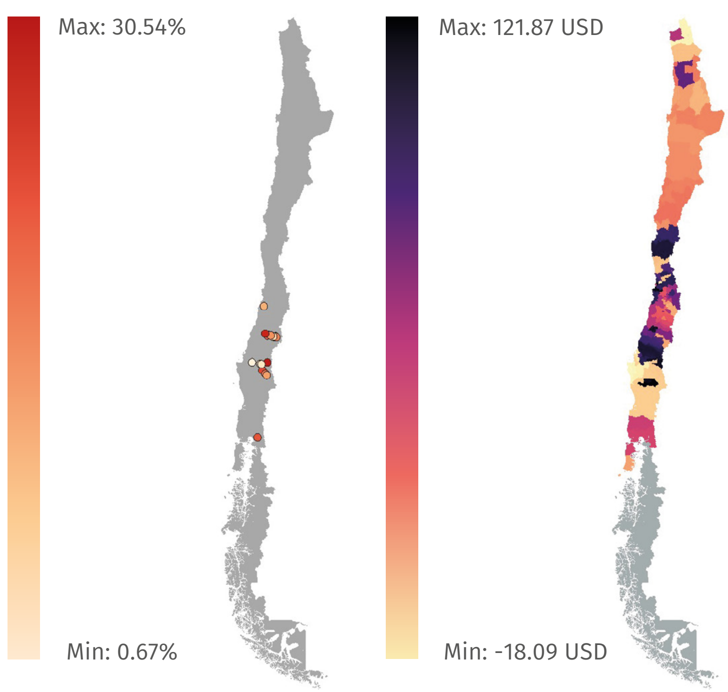
3.2.6. Climate change impacts on the Chilean electric power system

Given the trends mentioned above, a deep analysis of possible impacts on the National Electric System is necessary considering the current infrastructure and its projection, as well as the decarbonization route that has been proposed, for a long-term horizon. The project Climate Change Risk Maps for Chile, or ARClim (Pica-Téllez et al., 2020), presents various analyses on the impacts of climate change on the country, where in particular the analysis of the impacts of the variation of various climate-related factors on the Chilean Electric Power System were studied for a horizon extending over 2030-2065 under the climate scenario RCP8.5 (CMIP5) (Lorca et al., 2020). The factors studied include reduced water resources, which impacts hydropower availability, higher temperatures, which impacts power transmission capacities throughout the country, and the changes in wind and solar irradiation, which impact the availability and patterns of wind and solar power, respectively.

In the study, the methodology is based on the simulation of the operation of the current power system based on a model of centralized unit commitment and economic dispatch. These simulations evaluate the impacts concerning changes in marginal energy costs and the possible existence of non-supplied energy. For the analysis of the water resource, the variations in water inflows and the value of stored water of the main water systems with hydroelectric generation are considered as an input, the main ones being the Maule and Laja systems, which was obtained from the work by Vicuña et al. (2020), where a significant reduction in the future availability of water resources is determined. The available information is used to establish restrictions in the operation of the reservoir and run-of-river power plants, considering the correlation between the plants of the same system and the related inflow restrictions. The simulation takes the variation of the water resource independent of other types of uncertainty.

Based on the above, as shown in the study, hydroelectric generation is 20.6% lower considering the 2050 scenario, with a greater effect in the central and southern areas of the country. Furthermore, the resource variation has an incidental effect on the entire operation of the electricity grid, raising marginal hourly costs by an average of 26.5 USD/MWh over the annual average (from 45.5 to 72.0 USD/MWh). It is important to emphasize for this analysis the estimated electrical system for the year 2023 is considered, under the expected climate for the year 2050, compared to the current climate, which constitutes a climate sensitivity for a fixed electrical system and not an estimation of the energy prices for year 2050. The hazard map (Figure 10) shows that in some points, hydroelectric generation will decrease by up to 30.5%. In contrast, the sensitivity map shows that changes induced by climate change on hydrological regimes can imply an increase of up to 121 USD/MWh in some sectors of the country.

Figure 10
Hazard (left) and sensitivity (right) maps associated with the water availability variation event
Source: ARClim.



Most of the Chilean territory is projected to further increase mean annual temperatures between 0.5-1°C in both scenarios considered, except over the Altiplano and the *Atacama Desert*, where the increase is projected to reach between 1-1.5°C if we follow the high emission scenarios SSP5-8.5. In the case of precipitation, the region is projected to show a precipitation decrease, which is, however, statistically non-significant. In the Coquimbo region (central part of Chile), an increase in solar radiation is associated with an increase in solar energy supply.

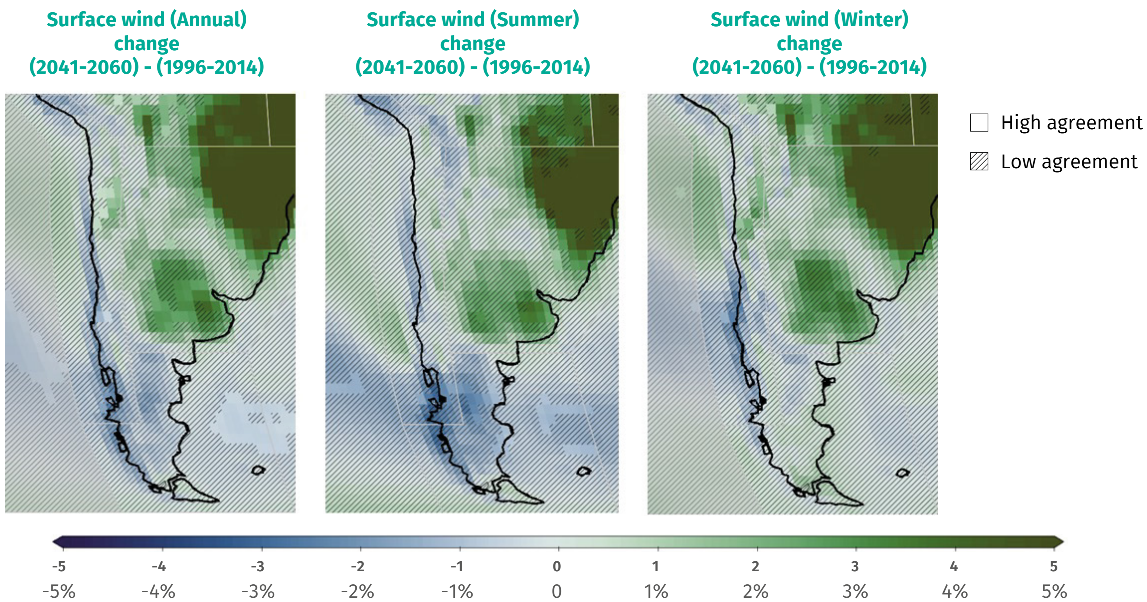
Another important impact on electrical energy supply is the limiting of the transmission capacity. The ARClim study positions this threat to be very high for two regions in the north of Chile, while low to moderate to the rest of the country.

CMIP6 simulations also project an increase in winds over the Atacama Desert. In the north part of Chile, the wind speed change is expected to have no significant impacts (Figure 11).

Figure 11

CMIP 6 projections of surface wind change (%) in the near term (2021-2040) relative to 1995-2014 on the SSP5-8.5 scenario

Source: Interactive Atlas, IPCC WG1, 2021.



In the CMIP 6 projections, the *Biobio region*, as most of the Chilean territory, is projected to further increase mean annual temperatures between 0.5-1°C and decrease total annual precipitation between 5-10% in the near to mid-term (Figures 8 and 9). CMIP 5 models predict a similar decrease in precipitation (Araya-Osses et al., 2020). The ARClim model positions hydric shortage as a high threat to Biobio's power generation potential as some hydraulic power plants are predicted to decrease their generation potential by 30%.

In the ARClim model, the solar radiation of the Biobio region is expected to increase by approximately 4.6 W/m². Despite this increase in solar radiation, the levelized cost of solar energy in this region is predicted to have low variations in the near term (less than 1 USD/MWh between 2035-2065). On the other hand, mean wind velocity is expected to decrease, hence lowering wind energy production by 1.3% in Los Maitenes wind farm as an example. However, the levelized cost of wind energy will not be affected by more than 1 USD/MWh. According to the ARClim, there is a high threat of replacing wind energy with more expensive alternatives in the near term for central Chile, especially in the Los Lagos region, where wind energy production is predicted to decrease as much as 2.7%.

The *Magallanes region* features a maritime climate, with annual mean temperatures of around 5-10°C and about 5°C differences between summer and winter. It is characterized by year-round precipitation, of about 500mm, a tiny annual cycle, and relatively small interannual variability (Boisier et al., 2018). The region is under the year-round influence of the southern westerly winds, with peak wind magnitudes during summer (Garreaud et al., 2013). Over the period 1979-2018 the region has seen positive temperature trends of the order of 0.1-0.2°C per decade (Figure 9), which is statistically significant only in some parts of the region. In recent years, there has been a significant decline in the snow cover (Cordero et al., 2019), which is correlated to a statistically significant winter warming of Punta Arenas (0.71°C between 1972-2016). In terms of precipitation, in most parts of the region, data show small increasing precipitation trends (10 to 20 mm per decade), again, most of which are not statistically significant. There is also widespread glacier mass loss associated with the warming and snow decline along the Andes, including southern Patagonia (Braun et al., 2019; Dussaillant et al., 2019). Future projections indicate further warming, although at a slower rate than the global average and the rest of the country (Figure 9). CMIP5 and Cordex simulations project a slight increase in precipitation under a low and high GHG concentration scenario (Bozkurt et al., 2019). For the near future, there is a small (statistically non-significant) precipitation decrease.

CMIP6 simulations also project a decrease in winds over most of central and southern Chile, including Magallanes. Over Magallanes, this is especially true for the summer season (December to February) when winds are strongest. Variation in wind speed can negatively affect wind energy generation (Figure 11). We must note that there is still no information in the ARClim on how wind speed will affect wind power generation in the Magallanes region. Finally, it should also be noted that there are no public studies that formally address the effects of extreme weather conditions resulting from the climate change we are experiencing (heat waves, torrential rains, floods, strong winds, among others).

In the following sections, each export option is discussed in more detail. Along with a description of the type of export, selected topics are analysed according to the different factors of analysis mentioned. It is worth mentioning that there are aspects that are repeated for more than one type of export. However, it has been decided to describe the topic in only one section and to mention it in the following sections if it applies.

3.3. Electrical interconnections

3.3.1. General technical description and economics

Electrical interconnections refer to power transmission infrastructure and control that allows transferring electrical power between different cities, countries, and even continents. These transmission systems are a key enabler for any country willing to export electricity (renewable or not) outside its borders.[16]

These systems are mainly composed of high voltage lines (overhead) and/or cables (underground or submarine), substations, monitoring, control, and protection equipment. Lines and cables enable electrical power transmission between substations, which are points of connection that allow for switching and voltage level transformation. There are two main technologies for electricity interconnections, using alternating current (AC) or direct current (DC). To transmit the same amount of power, DC power lines need fewer conductors and, thus, thinner structures, making them cheaper. However, DC substations are much more expensive than their AC counterparts. Then, there is a distance where DC systems become more cost-effective than AC (the extra cost on substations is less than the savings in power lines), which can be around 800-1,000 km and 50 km for overhead lines and submarine cables, respectively (Schavemaker & Sluis, 2008). High voltage DC (HVDC) systems also enable connecting countries operating at different electrical frequencies (50 and 60 Hz), such as the existing interconnection between Brazil (60 Hz) and Argentina (50 Hz).[17] This section discusses alternatives for enabling the export of renewable power from Chile to neighbouring countries.

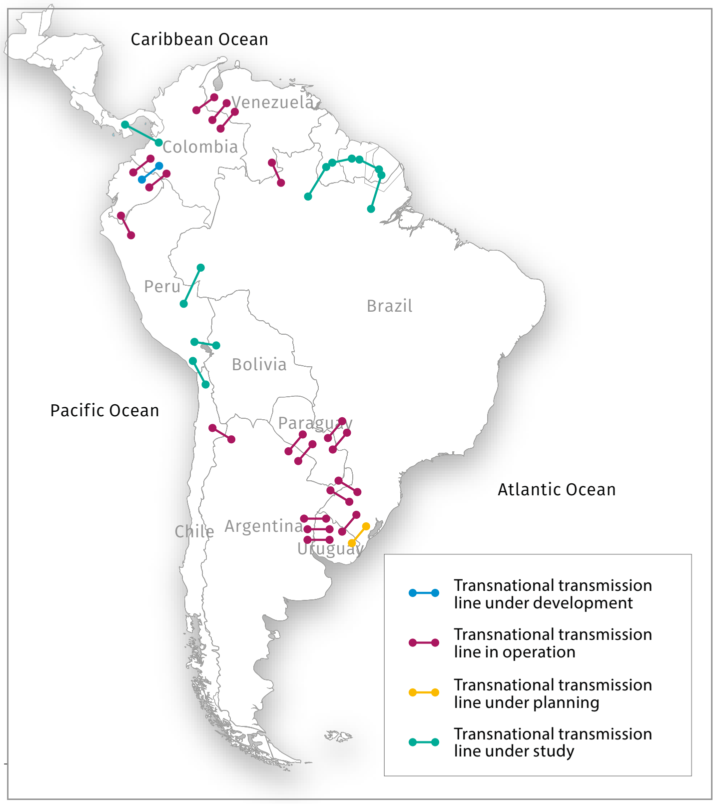
For power generation systems to shift from a fossil fuel-based generation to a RE mix and maintain their reliability, new electrical interconnections must be built, and old transmission interconnections must be upgraded simultaneously (Shen et al., 2018). Along with the possibility of exchanging RE among different zones, the main technical advantage of electrical interconnections is the consequent improvement in the electricity system's reliability. When a power plant fails, or during extreme weather conditions, interconnections can help keep the lights on (balancing power). This feature improves the security of supply, reduces the risk of blackouts, reduces the need for building new power plants, and makes it easier to manage less predictable renewable power sources such as solar and wind (Aghahosseini et al., 2019; European Commission, 2017).

The possibility of extending electricity interconnections at the regional level has been addressed in several studies (Aghahosseini et al., 2019; Agostini et al., 2019; Barbosa et al., 2017; BID, 2017; Blanco, 2021; Sauma et al., 2011). In the case of South America, transmission lines are limited and are based on bilateral agreements, with only 19 projects built to date and three more under planning or study. Figure 12 summarizes this scenario.

16 https://ec.europa.eu/energy/topics/infrastructure/electricity-interconnection-targets_en.

17 See https://www.hitachiabb-powergrids.com/africa/en/references/hvdc/brazil-argentina-hvdc-interconnection.

Figure 12
Interconnections in South America
Source: Liu (2015) and CIER.



For the case of Central and South America, new HVAC/DC transmission expansions between sub-regions will enable a significant decrease in RE and storage installed capacities in the RE-based system (Aghahosseini et al., 2019; Barbosa et al., 2017). As a general conclusion of these analyses, there is a significant potential for economic exchanges in energy production in Latin America. This is also the case for the export of solar energy from Chile with about 50 GW of installed capacity by 2050 (Blanco, 2021).

In this context, it is worth mentioning the GEIDCO project, whose purpose is to promote the establishment of a Global Energy Interconnection (GEI) system to meet the global power demand with low-carbon and renewable alternatives, using HV long-distance interconnections. According to GEIDCO's strategy, by 2050, the American continent would be interconnected; and by 2070, nine horizontal and nine vertical power lines would connect the globe.[18]

According to Jimenez-Estevez et al. (2015), solar resources in Chile can not only fuel sustainable development in Chile but also supply electricity for export to other South American countries. In this scenario, foreseen for 2035, 30% of the electricity consumption in South America can be supplied by solar energy plants located in the Atacama Desert with a total installed capacity of 200 GW; which represents less than 1% of the Chilean continental surface, not quite 5% of the available space in the Atacama Desert (Jimenez-Estevez et al., 2015) and about 10% of the total technical potential of solar PV. According to Barbosa et al. (2017), by 2030, Chile would be a net exporter of renewable electricity towards Peru, Bolivia, and Paraguay, while the net electricity exchange with Argentina would be zero.

Electricity exchange between cities, countries, or continents via large electricity transmission networks is a commonly discussed solution to tackle the variability of RE sources. According to several studies applied to different parts of the world (Aghahosseini et al., 2017, 2019; Bogdanov et al., 2019, 2021; Bogdanov & Breyer, 2016; Child et al., 2019; Jacobson, 2021), HVDC power lines have been the most utilized structure in continental interconnection and it has been assumed that most of the new interconnection transmission lines between countries in the future will be built with this technology. These studies have also identified

18 https://en.geidco.org.cn/aboutgei/strategy/.

that the main technical challenges can be categorised as follows: control systems from both security and reliability perspectives, network complexity, and power grid congestion. Importantly, the rapid control of HVDC interconnectors can also facilitate the delivery of advanced security services, related to system stability (Pipelzadeh et al., 2017).

The total LCOE under continental interconnection scenarios, in addition to electricity generation costs presented in previous sections, must include LCOS (storage), LCOC (curtailment), and LCOT (transmission) in the analysis. In this sense, most of the continental interconnection studies carried out in different parts of the world have shown that the installation of an HVDC transmission grid between countries enables a significant decrease not only in the total LCOE but also in RE and storage installed capacities (Bogdanov et al., 2019; Bogdanov & Breyer, 2016; Child et al., 2019; Jacobson, 2021). According to (Child et al., 2019), greater cost savings can be achieved through the establishment of increased interconnections. In fact, interconnecting countries reduces annual costs further by reducing storage requirements and excess generation nameplate capacity (Jacobson, 2021). All of these cost reductions have also been found in the case of Central and South America interconnected scenarios (Aghahosseini et al., 2019; Barbosa et al., 2017). Moreover, it is feasible to export surplus electricity today from Chile to Argentina under the current regulatory schemes of both countries and the transmission capacity already built (Agostini et al., 2019).

Despite the benefits of international interconnectors, two critical aspects may impede its efficient development in practice. One is the conflicting incentives of member states in a region as costs and benefits of new interconnectors may not be appropriately distributed/allocated among them. Also, the presence of deep uncertainty in the development of system expansions in different countries (characterized by severe uncertainty in policies, costs, future generation fleet, renewables investments, demand growth, electrification, etc.) may introduce extra risks in the decision-making process of new interconnectors, ultimately threatening their efficient deployment (Konstantelos et al., 2017).

3.3.2. Environmental impacts

The environmental impacts of the construction of overhead HVDC or AC transmission lines are broad and can be both detrimental and beneficial. The main beneficial effect is the increased access to RE. Grids that gain access to cleaner, renewable power generation plants can significantly reduce the overall carbon footprint and other emissions associated with a region (Otsuki, 2017). The creation of a GEI system using HVDC supposes an overall improvement of the global environmental situation by making possible the redistribution of power generation towards exporting countries with considerably more renewable resources and decreasing energy production in demanding countries with unfavourable environmental conditions (Voropai et al., 2018).

However, to maximize the environmental benefit of extending electrical interconnections, disadvantageous impacts on the construction, operation, and maintenance of overhead power transmission lines, substations, and converter stations must be minimized. The most significant detrimental environmental impacts can be summarized as; 1) Land use changes; 2) Biodiversity impacts; 3) Hydrologic impacts; 4) Soil erosion; 5) Contamination by pesticides; 6) Audible noise. Many environmental concerns arise from keeping transmission lines clear of ground obstacles and aerial structures. For example, agriculture can be affected by eliminating cropland; forests can suffer from permanent removal of woody vegetation, wetlands can be disrupted, the soil could be compacted and eroded, and the hydrology of water bodies can be altered. In addition, habitat fragmentation, constant noise, inadequate wastewater and residue treatment for construction camps, pesticides, and leakages from pieces of equipment, can pollute surrounding ecosystems and negatively affect biodiversity in sensitive areas (UN, 2007; Williams, 2003).

In the case of the use of underground or ocean power cables for HVDC, such as those contemplated in GEIDCO, temporarily or permanently impact to the marine environment are of concern; habitat damage or loss, noise, chemical pollution, heat and electromagnetic field emissions, risk of entanglement, the introduction of artificial substrates, and the creation of reserve effects (Taormina et al., 2018).

3.3.3. Social topics

Large interconnection systems can also have negative socio-environmental impacts. In some isolated communities (e.g., in Aysén), large transmission structures cross territories where local communities are poorly connected or totally disconnected. It is not just an "aesthetic landscape" that is affected; it is a factor that reflects an environmental injustice that conspires against citizen support for projects that would benefit RE exports (Baigorrotegui & Parker, 2018). In other words, there are not only environmental impacts; there are also socio-cultural impacts. There is local resistance to hydropower development, particularly in indigenous territories (Höhl, 2018; Kelly, 2019).

One important aspect that amplifies the socio-environmental impacts of transmission networks is its uncoordinated expansion, where many participants (planning authority and companies that develop new projects) invest in transmission lines on a project-by-project basis, without formal coordination. Also, the socio-environmental impacts in the transmission planning process are considered ex post facto, after the projects have been already determined/decided. A new body of work shows that including the potential socio-environmental impacts of new projects when identifying the set of new transmission lines (before deciding the final set of investments and attempting to anticipate their impacts) will significantly reduce the socio-environmental externalities of transmission (Matamala et al., 2019).

3.3.4. Institutional-legal topics

Since 2017, due to Law 20.936,[19] the Ministry of Energy can hire external consultants to study the best alternative for expanding the electric transmission network between two zones, the so-called "Estudio de Franjas". In order to determine the strips to be considered, the analysis should incorporate technical, economic, environmental and sustainable development criteria (Centro de Cambio Global UC et al., 2018), including early citizen participation and indigenous participation as established in the International Labour Organization (ILO) Convention No. 169.[20] However, these important considerations apply neither to all the electrical networks nor to other infrastructure developments that could be relevant for the success of electrical interconnection projects.

In addition, electricity exports must be consistent with the principles set out in Chile's climate-change policy. In fact, the main difference with previous interconnection projects in Chile is that most of the future projects will be subject to climate change policy, which involves social and environmental standards that were previously absent. In this sense, Law 20.936 can provide a framework close to the standards set out in the NDC and the FLCC on Climate Change, but further research is required to identify potential loopholes and shortcomings.

3.3.5. Political topics

Internationally, renewable technologies have reached a high level of competitiveness concerning other forms of electricity production. Consequently, a decrease in incentives through feed-in tariff or similar subsidised price programs has been observed (IRENA, 2021). In this context, a scenario of interconnection development without specific instruments for the RE sector is projected for Chile, concentrating the discussion on possible incentives in the transmission and storage sector.

On the other hand, so far, the strategy of interconnections based on bilateral agreements has predominated. There have been preliminary approaches towards the creation of a regional energy system based on multilateral agreements.[21] Moreover, the position of several countries is that of projecting themselves as energy exporters, which configures a scenario of competition rather than cooperation.

3.4. Green hydrogen

3.4.1. General description

Hydrogen is the simplest, lightest, and most abundant element in the universe. Due to its chemical ability to combine with most of the other chemical elements, molecular hydrogen rarely occurs as a product of biogeochemical cycles on Earth. Once produced through industrial methods, H_2 molecules can be combined with O_2 to release energy and form water, either by combustion in an internal combustion engine or by inducing an electric current in fuel cells.

Broadly speaking, green hydrogen is molecular H_2 produced with no GHG emissions, provided the energy used to power the process is entirely from renewables (Oliveira et al., 2021). However, given that the industrial system is currently based on fossil fuels, most goods and services are produced using a certain amount of non-renewable, hydrocarbon-based energy –including the equipment used to produce and transport green hydrogen. Since hydrogen initiatives regard H_2 as a means for climate change mitigation, the emission of GHGs in its life cycle is also relevant. In this sense, CertifHy (2015) has put forward a "share-based approach" that considers the following points: a) the share of green hydrogen in a given volume of produced hydrogen is proportional to the renewable-energy share used in the production of the total volume; and b) if the associated GHG emissions are lower than a certain predefined threshold, the hydrogen produced will be considered green.

Besides the production process, which is addressed in the following paragraphs, exporting green hydrogen also entails its transportation to the final user. Due to the geographical position of Chile in relation to the main importing centres, most of the transportation process would be carried out through tanker ships. Therefore, the challenges associated with maritime transport of H_2 will also be analysed in this section.

3.4.2. Technological topics

There are different methods to produce green hydrogen. However, water electrolysis (with electricity from RE) is the most widely accepted for green production of hydrogen by industry and different governments across the globe. Electrolysis processes can be carried out at low or high temperatures, depending on the technology used. Alkaline water electrolysis (AWE) or proton exchange membrane water electrolysis (PEMWE) works at low temperatures, while solid oxide water electrolysis (SOWE) works at high temperatures. Alkaline and polymeric electrolysers are commercially available, but there are opportunities for improvement. In alkaline electrolyser the alkalis use a corrosive liquid electrolyte, gases are produced at low pressure, and an H_2 purification step is

19 https://www.bcn.cl/leychile/navegar?idNorma=1092695.
20 https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_INSTRUMENT_ID,P12100_LANG_CODE:312314,en.
21 SINEA (Colombia, Ecuador, Perú, Bolivia) and SIESUR (Argentina, Brasil, Paraguay y Uruguay) for the promotion of electricity exchanges in the region (https://blogs.iadb.org/energia/es/un-paso-mas-hacia-la-interconexion-electrica-de-los-paises-de-america-latina/).

necessary (Fúnez Guerra & Reyes-Bozo, 2019). Challenges for PEM electrolysers are the costs of catalysts and membranes and the required water quality (Fúnez Guerra & Reyes-Bozo, 2019). A recent socio-technical review regards high-temperature electrolysis in a low technology readiness level (TRL) (Griffiths et al., 2021).

In addition to water electrolysis, hydrogen can be produced by thermochemical methods that use biomass as feedstock. Even though some of these methods may have large AP impacts and their efficiency is limited by metabolic pathways, it might be interesting to consider them as an option for the long run (see Environmental topics in this section).

Once produced, green hydrogen is stored under pressure. There are low-pressure systems, which are less expensive but require a larger surface area. For different applications, there are storage systems at higher pressures (350 bar, 700 bar, or higher). Compression technologies are already available on the market, as well as storage systems and hydrogen dispensers (Fúnez Guerra et al., 2018, 2021; Fúnez Guerra, Reyes-Bozo, Vyhmeister, Jaén Caparrós, Salazar, & Clemente-Jul, 2020).

Finally, hydrogen can be used for storage to produce electricity in another period of time. Currently, observed efficiencies of the complete process are around 50%. This could make sense if the price differential between day and night is large enough (energy arbitrage: excess solar energy can be stored during the day, stored as H_2, and then used to produce at night to displace fossil fuel generation). In this case, it is worth considering whether there are other more efficient means of storage, such as pumped storage plants or batteries (lithium, REDOX, etc.).

3.4.3. Environmental topics

According to IRENA (2020), the shift from a fossil fuel-based economy to a green hydrogen economy could significantly mitigate the anthropogenic CO_2 footprint and keep the rising temperature below the maximum target of 1.5°C. The most feasible scenario where an energy transition is genuinely sustainable is implementing a 100% RE matrix that completely replaces fossil fuels, in which green H_2 will play a significant role (Osorio-Aravena et al., 2021). The mitigation potential of this substitution depends on the production methods available, as the GWP varies greatly among the different pathways for obtaining hydrogen.

Besides GWP, there are other environmental aspects of green-hydrogen production to consider, such as the impact on biodiversity (infrastructure involved), AP, eutrophication potential, recyclability of materials, desalination plant impacts, among many others. These metrics should consider the whole value-added chain (from production to consumption) through a harmonized LCA or a planetary boundary approach. Most of these studies do not include the export of the final product before consumption; hence the environmental impact of different export methods will be presented separately.

Studies that used LCA methodologies to investigate the environmental performance of the different hydrogen production methods have found that hydrogen produced by wind or solar-based electrolysis is a more environmentally benign option compared to conventional natural gas steam reforming (Ozbilen et al., 2013). Hydrogen produced through fossil-fuel gasification or reforming (currently the most widespread method for obtaining hydrogen) has a GWP between 9 and 12 $kgCO_2eq/kgH_2$ (Acar & Dincer, 2015; Iribarren et al., 2021; Ozbilen et al., 2013). Since the emissions of CO_2, CO, SOx, hydrocarbons, and particulates are practically eliminated in the operation of a solar-to-hydrogen system, the environmental impact of this process is 23 times lower than that of fossil-fuel hydrogen production (Baykara, 2018). In addition to high GWP, transportation risks (spills in the oceans), massive environmental damage due to the extraction of fossil fuels, and natural-resource depletion make these latter methods unsustainable in the long term (Baykara, 2018). Nevertheless, the application of carbon sequestration, autocatalytic decomposition, and hybridization with solar thermal processes may mitigate emissions and keep fossil-based hydrogen production competitive (blue hydrogen) against green hydrogen in the midterm (Dufour et al., 2009).

Since terrestrial biomass is a renewable, affordable, and abundant source of energy in the country (Gaete-Morales et al., 2018), methods based on this energy source are also an available option for producing hydrogen in Chile in the long term. Much of this biomass is currently being discarded as waste (like water treatment sludge or agricultural residues). Autothermal biomass gasification and reforming processes could achieve low environmental impact when coupled with carbon storage systems. As recommended by the IPCC, the residual biochar from pyrolysis methods could also be applied in the farming fields to provide a carbon sink and improve crop yield (Olsson et al., 2019). Depending on the carbon residues management, GWP of biomass gasification/reforming can vary greatly; it has been evaluated as low as 0,18 $kgCO_2eq/kg\ H_2$ (for a case of poplar gasification), and as high as 24,19 $kg\ CO_2eq/kgH_2$ (Acar & Dincer, 2015; Dincer & Acar, 2015; Iribarren et al., 2017; Ozbilen et al., 2013).

While the GWP of biomass-based hydrogen can be kept at its minimum when best practices are applied, the AP of biomass reforming and gasification has the highest impact on the environment of all H_2 production methods in general with 29,03 gSO_2eq/kgH_2 (Acar & Dincer, 2015; Iribarren et al., 2019), even when compared with coal gasification, which has an AP of 12-24,2 gSO_2eq/kgH_2 (Ozbilen et al., 2013; Siddiqui & Dincer, 2019). Unfavourable AP performances of thermochemical biomass conversion are due to the intensive fertilizer use associated with the production of most biomass resources. This concern can be addressed by replacing fertilizers with the residual digestate of the anaerobic production of biogas; in these cases, biomass gasification can potentially lead to negative AP values (Iribarren et al., 2017).

Other biomass-based methods that present considerably lower environmental impacts than the traditional gasification/pyrolysis methods are the photocatalytic degradation of organic waste matter and dark fermentation (when organic material is de-composed by anaerobic bacteria in absence of sunlight). Fermentation methods yield a GWP between 0,5 and 7,36 $kgCO_2eq/kgH_2$ (Dincer & Acar, 2015; Iribarren et al., 2017) and a very low AP of 0,4 gSO_2eq/kgH_2 (Acar & Dincer, 2015). However, these methods are currently in a developmental stage and their efficiency is limited by metabolic pathways.

Caliskan et al. (2013) have estimated that the CO_2 emissions of wind-powered electrolysis are approximately 20% lower than those of PV panels. Onshore wind power generation has the largest and proven potential in Chile, however exporting energy from the region could be a potential future market to also develop offshore wind energy (Mattar et al., 2021). Harnessing offshore wind can be also both beneficial and detrimental to biodiversity, as the aerial part of windmills can disturb the migration patterns of seasonal birds while at the same time, the underwater structure can create artificial reefs to enhance submarine ecosystem development (Pörtner et al., 2021).

LCA studies have shown that electrolysis processes powered by electricity from RE sources have low GWP (usually less than 5kg CO_2eq/kgH_2), and that wind electrolysis has the lowest index (less than 1 kg CO_2eq/kgH_2) (Dincer & Acar, 2015; Iribarren et al., 2019; Siddiqui & Dincer, 2019). Iribarren et al. (2017), estimates the GWP of PV electrolysis between 2.18 and 7.54 $kgCO_2eq/kgH_2$. Using energy from non-renewable sources, these values could be as high as 30kg $CO_2/kg\ H_2$ (Baykara, 2018). Siddiqui and Dincer (2019) assessed the environmental impact of some hydrogen production routes that are based on a well-to-pump life cycle: they found that electrolysis using the US 2018 energy mix has a GWP of 27.3 $kgCO_2/kgH_2$ life-cycle emissions –even higher than coal gasification.

Hydropower is sometimes considered another option of RE source for hydrogen. However, large hydropower projects have historically sparked conflicts in Chile due to socio-environmental issues. They are now not regarded as entirely sustainable due to the potential harm to biodiversity caused by its infrastructure (Osorio-Aravena et al., 2021). In addition, to the best of our knowledge, there are no empirical studies that quantify GHG emissions of hydropower reservoirs in Chile. In spite of these considerations, currently existing hydropower plants could supply RE to perform electrolysis. Likewise, Chile's hydroelectricity can provide pressurized water for electrolysis using inland water. This topic has not been studied in depth either.

Another green hydrogen production method relevant for Chile is based on thermochemical reaction cycles. Since the chemical compounds involved in the process can be recycled in a closed-loop, this is a promising way of producing green hydrogen (Acar & Dincer, 2015). For the produced hydrogen to be considered "green," the thermal energy source needed to drive individual reactions in the cycle must be renewable. Concentrated solar, biomass and geothermal can be listed as possible sustainable thermal energy sources (Baykara, 2018; Dincer & Acar, 2015). We must note that the nuclear-based four-step Cu-Cl cycle has a very low GWP with 0,56 kg $CO_2eq/kg\ H_2$ (Ozbilen et al., 2013). Since the use of nuclear energy as a thermal source has an inherent risk to environmental and human health, some studies do not consider this energy to be sustainable in Chile (Osorio-Aravena et al., 2021).

According to Baykara (2018), hydrogen produced from water and terrestrial biomass using solar and wind energy will be the most sustainable energy currency in the long term.

Most of the hydrogen produced in Chile is expected to employ seawater as the main input for electrolysis. Large desalination plants must be constructed to perform reverse osmosis and supply enough freshwater to feed hydrogen production.[22] Desalination plants construction, operation, and maintenance present several environmental stresses of concern, such as noise, land modification, disruption of water currents, and more notoriously, adduction pipelines, and effluent discharge (brine, chemicals and heavy metals). These stresses produce undesired environmental impacts such as reduced primary production, habitat reduction and alteration (community composition alteration), benthic community disruption, avoidance behavior of organisms, and plankton/larvae growth impairment (Seyfried et al., 2019).

The spatial footprint of the discharge plume is more accentuated in the floor bed than near the surface, and its impacts may extend up to 600 m offshore, increasing salinity up to 3-5% above historical ambient salinity, depending on the specific hydrodynamics in the discharge area (Petersen et al., 2019). Worldwide observations of desalination facilities have linked a decrease in epi- and infaunal organisms due to an increase in 5% salinity in seawater (De-la-Ossa-Carretero et al., 2016; Frank et al., 2017; Sánchez-Lizaso et al., 2008). Furthermore, typically reverse osmosis effluents also contain other pollutants such as chlorine (used to control biofouling and prevent membrane damage), coagulants (to remove suspended solids), antifoaming agents, heavy metals (due corrosion of materials), and cleaning chemical compounds (Lattemann & Höpner, 2008).

To protect the dynamics of coastal ecosystems, hazardous additives must be replaced by alternative treatment options, and the output should be treated before discharge. Biocides such as chlorine, which harm non-target organisms in the discharge site, are of special concern. Available treatments such as sedimentation or land deposition, building special treatment facilities, or discharge to sanitary sewer systems could significantly reduce potential damage to marine ecosystems. In addition, to minimize the detrimental effects of brine discharge, the effluent must be mixed and pre-diluted before the discharge stream is rejected. This can be done by installing a diffuser system and locating the release pipe away from biodiversity hotspots, local fisheries, and considering only the most favourable oceanographic sites (high energy sites where salinity and heat can be quickly dissipat-

22 CE-FCFM Universidad de Chile, UTA: "Identificación de zonas para el desarrollo de proyectos integrales de agua y energía, CE-FCFM Universidad de Chile", GIZ, 2020.

ed). Simulation models of the brine plume dispersion have revealed the inadequacy of using surface discharging outfalls, while submerged discharges ensure a higher dilution, reducing harmful impacts on the marine environment (Peters & Pintó, 2008). Finally, to safeguard the sustainable use of desalination technology, the effects of desalination plants should be investigated and mitigated through environmental impact assessments (EIA), while considering local biodiversity and regional management plans (Lattemann & Höpner, 2008).

In 2019, eleven desalination plants were operating in Chile, producing 5,868 l/s of desalinated water, and ten more projects were in different stages of evaluation, which will double the production of desalinated water (Herrera-León et al., 2019). Despite the growing desalination industry, there is no regulation in Chile regarding the effluent discharge of desalination plants to the coastal zones.

3.4.4. Social topics

The literature related to the conflict potential of hydrogen projects in the country is practically non-existent. Still, it can, a priori, be associated with energy projects due to their production chain. In recent months, different texts have been published in the media, highlighting some social issues associated with this new green hydrogen industry. For example, the Latin American Observatory of Environmental Conflicts (OLCA) published a report on the risk of adverse impacts that this productive sector could generate in the territories where the projects are located. The issues addressed in the report are water use, the installation of desalination plants, and the construction of large renewable generation fields and transmission networks, deepening the "extractive" model[23] (see section 4.2.1).

By contrast, the need to explore ways in which green hydrogen production can directly benefit citizens under a more decentralized production model has been addressed.[24] Injecting green hydrogen into the natural gas networks that supply energy to households could be regarded as a way to link this vector to the citizens. In addition, hydrogen is seen as a complementary energy source to natural gas that could reduce emissions in the residential sector (Ministerio de Energía, Gobierno de Chile, 2020), and eventually replace it. EU countries and Australia, mainly, have initiated pilot projects with varying degrees of progress (Torres Vásquez et al., 2021), and recently Chile announced a similar initiative in the Coquimbo region.[25]

However, research has found that an energy transition to hydrogen could create or reinforce existing conditions of inequality in hydrogen distribution or exacerbate conditions of energy vulnerability or energy poverty in specific community sectors (Aas et al., 2020; Committee on Climate Change UK, 2018; Sandri et al., 2021; M. Scott & Powells, 2020). In addition, there is a risk that the cost of new infrastructure and grid upgrades will be passed on to consumers, either through increased tariffs via taxes (M. Scott & Powells, 2020) or through an eventual process of replacing household appliances suitable for hydrogen use (Committee on Climate Change UK, 2018; Sandri et al., 2021; M. Scott & Powells, 2020). On the other hand, Scott and Powells (2020) argue that hydrogen as a complement or replacement for natural gas could impact cultural patterns and practices in cooking and heating households.

The socialization of new socio-technical knowledge involving the installation of hydrogen-based energy systems must consider the progressive overcoming of knowledge asymmetries (Parker & Pérez Valdivia, 2019) if the aim is to avoid conflicts and stimulate citizen participation.

3.4.5. Economic topics

The cost of green hydrogen production is site-specific and depends on each geographical area, being a function of the quality and quantity of renewable resources. Case studies show that the price of renewable electricity is a key factor in producing green hydrogen (Fúnez Guerra et al., 2018, 2021; Fúnez Guerra, Reyes-Bozo, Vyhmeister, Jaén Caparrós, Salazar, & Clemente-Jul, 2020; Fúnez Guerra, Reyes-Bozo, Vyhmeister, Jaén Caparrós, Salazar, Godoy-Faúndez, et al., 2020; IRENA, 2020a; Vyhmeister et al., 2017). Other key variables for its economic competitiveness are the cost of the electrolyser and the full load hours. Depending on the site-specific variables of each study case (operating hours, diesel price, electrolyser design, economies of scale, etc.), if electricity prices are below 60 €/MWh, a positive NPV could be obtained (Fúnez Guerra et al., 2021; Fúnez Guerra, Reyes-Bozo, Vyhmeister, Jaén Caparrós, Salazar, Godoy-Faúndez, et al., 2020). If the electricity price variable is studied alone, a price of 20 USD/MWh ensures a competitive price for green hydrogen (IRENA, 2020a).

According to IRENA (2020a), green hydrogen currently costs between two and three times more than blue hydrogen, produced using fossil fuels in combination with CCS. IRENA's report highlights that falling renewable power costs and improving electrolyser technologies could make green hydrogen cost-competitive by 2030. In fact, on the one hand, the share of PV electricity cost in the $LCOH_2$ represent more than 60%, and, on the other hand, electrolyser CAPEX for a large utility-scale system is expected to decrease from current 400 €/kW_{el} to 240 €/kW_{el} by 2030 and to 80 €/kW_{el} by 2050 (Vartiainen et al., 2021). In this

23 https://radio.uchile.cl/2021/08/28/hidrogeno-verde-o-como-profundizar-el-extractivismo-parte-i/.
24 https://www.ciperchile.cl/2021/05/29/hidrogeno-verde-en-chile-la-gran-oportunidad-para-crear-un-modelo-de-desarrollo-ejemplar/.
25 https://energia.gob.cl/noticias/nacional/primero-en-chile-y-america-latina-ministro-jobet-anuncia-el-primer-proyecto-que-inyectara-hidrogeno-verde-en-redes-de-gas

sense, Chile has been identified as one of the countries with sites that have the lowest costs for green hydrogen production based on hybrid PV-wind power plants (Fasihi & Breyer, 2020). According to Fasihi and Breyer (2020), in the Atacama desert and Patagonia, green hydrogen can be produced at less than 66, 48, 40, and 35 €/$MWh_{H2,HHV}$, in 2020, 2030, 2040, and 2050, respectively, for 7% WACC. However, depending on the learning curve of key technologies and market conditions, green hydrogen production costs could be even lower in the long term (Vartiainen et al., 2021). Furthermore, hydrogen producers can even benefit from renewable generation curtailments driven by network congestion, which are envisaged to be higher in the north of Chile because of the decreasing costs of PV investments and the increasing costs of (and difficulties to develop) transmission networks (Moreno et al., 2020).

The business model for RE will depend on the government's interest in developing RE, governance and policy support, and ease of doing business. Thus, the business model will depend on each country (Gabriel & Kirkwood, 2016).

By 2030, if large-scale transportation and production infrastructure are in place, green hydrogen could be shipped from places like Australia, Chile, or the Middle East to projected demand centres at the cost of USD 2-3/kg of hydrogen. This cost, which considers different transportation routes and different energy carriers (e.g., ammonia, methane, methanol, liquid hydrogen, etc.), coupled with increasingly lower hydrogen production costs, will allow for increased demand in hydrogen importing countries in many key sectors, such as transportation, industry, feedstock use, among others (Hydrogen Council, 2021).

3.4.6. Institutional-legal topics

Griffiths et al. (2021), in their systematic review of more than 700 publications on hydrogen production and utilization across multiple industries worldwide, identify a series of public policies related to hydrogen that has been promoted over the last decade, mainly in the EU countries and Australia. These policy toolkits have been built on RE policy frames, so the authors remark the need for specific instruments aimed at hydrogen development. Currently, in Chile, national regulation on hydrogen is generic and it is included in the regulation of hazardous substances, specifically, about transport and storage safety issues (Centro de Energía UC, 2020). A recent report by Centro de Energía UC (2020) identifies the need for modern regulation that guarantees the safety of people, infrastructure and places, in order to develop new hydrogen projects and speed up the permit process.

According to the classification in Griffiths et al. (2021), there are three types of measures related to H_2 in different countries: a) policies for promoting public and private investment in technology and R&D; b) regulatory policies; and c) fiscal incentive and public financing. In the first group, there are measures to foster direct research funding at universities and other academic institutions and public-private partnerships for project demonstration. The regulatory policies target different areas like standards and regulation on CO_2 emission, energy use, electricity generation, environment, and safety; also includes hydrogen quality and performance, certification schemes and codes for infrastructure building, and zoning. Finally, according to the authors, the fiscal incentives are related to price controls, government procurement; contract for difference; carbon pricing, taxes and trading schemes; energy subsidies and tax rebates and subsidies, among others.

Several institutions have identified the barriers at the international level that must be addressed for the widespread adoption of hydrogen as an energy carrier (European Commission, 2020; Hydrogen Council, 2021; IEA, 2019; IRENA, 2020b). They point out the need for major technology deployment, a proper infrastructure, lower costs, enhanced supply chains, tackling energy losses, and the development of an international hydrogen trade system. In the renewable hydrogen or green hydrogen case, the International Renewable Energy Agency (IRENA) has added the lack of value recognition in a world where there is no green hydrogen market, the need to ensure the sustainability that keeps the "green" at any given moment, particularly in those projects that use grid electricity for hydrogen production. Griffiths et al. (2021) also identify the absence of a clear definition of what is going to be considered as "green hydrogen" in the regulatory and policy frameworks, and the need for certification schemes to be applied to the production pathway.

3.4.7. Political topics

Since 2018, different countries have developed national hydrogen strategies. It is worth mentioning that this process is recent and very dynamic. As of September 2020, twenty countries already had or were close to publishing a national hydrogen strategy, and another 31 countries were supporting national projects and discussing policy actions (Albrecht et al., 2020). In the search for related information, a distinction is made between R&D programs, vision documents, roadmaps and strategies themselves. All these initiatives present varying levels of depth and support. They contain relevant information that also reflects the political dimension of each strategy. For the purposes of this analysis, the hydrogen strategies of the following countries have been reviewed: Australia, Canada, France, Germany, Japan, the Netherlands, Norway, Portugal, Spain and the USA. Of all these, only Australia, Canada and Spain explicitly state hydrogen export strategies. Their key features are summarized below.

Australia:[26]

26 National Hydrogen Roadmap, Pathways to an economically sustainable hydrogen industry in Australia, https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-roadmap.

- Export potential to Japan, China and Singapore: 3.8 million tons in 2030.
- Target hydrogen production price of 2-3 USD/kg to compete with other exporting countries.
- Implement bilateral export agreements to give confidence to the industry.
- Establish a 'take or pay' contract modality.
- Negotiate favourable tariffs for hydrogen exports (including in existing FTAs).
- Implementation of regulations that support the use of unused land for the development of dedicated NCRE and electrolysers.
- Engage bodies such as the International Maritime Organization (IMO) to ensure appropriate regulatory frameworks for hydrogen transport.
- Establish long-term purchase or sale agreements.
- Install production plants near existing export terminals where possible.

Canada:[27]

- Five potential export markets: USA (California and the Northeast), Japan, South Korea, China and the European Union.
- New export markets may also be developed in South America.
- Develop a strong Canadian brand, positioning Canada as a global supplier of low-carbon hydrogen and the technologies to use it.
- Establish national flagship projects that highlight Canada's expertise, attract investment in the domestic market, and can be replicated internationally.
- Engage existing international forums (such as the Clean Energy Hydrogen Ministerial Initiative, G20, IEA) to show Canada's leadership, and promote new market opportunities.
- Significant near-term actions are required to secure Canada's supply-chain position in global markets (i.e., adjustments of bilateral agreements, participation in the development of standards).
- Ensure that Canadian hydrogen production is supported by a certified life-cycle analysis.
- Participate in ongoing international development efforts to establish thresholds and certify compliance with fuel standards.
- Bilateral alignment of standards and certification with the US for hydrogen export on existing pipelines.
- Identify and promote the development of enabling infrastructure for the sector.

Spain:[28]

- In collaboration with European institutions, establish a system of Guarantees of Origin for renewable hydrogen to provide appropriate price signals to consumers.
- Establish a legal basis for Power-to-X (P2X) power plants and electrolysis facilities.
- Encourage the active participation of Spanish companies in the International Standardization Committees related to renewable hydrogen.
- Encourage dialogue with Portugal, France and other EU countries to promote regional cooperation in the field of renewable hydrogen under European mechanisms such as the Connecting Europe Facility (CEF), favouring the positioning of the Iberian Peninsula in the production of renewable hydrogen and the potential supply of future surpluses to other EU Member States.

From these strategies, the following political dimensions can be highlighted:

- The State plays a major articulation and leading role to generate a favourable context for the development of this industry, particularly in the space of international negotiations of bilateral or multilateral nature, as well as in the negotiation of contracts and market positioning.
- Seek to influence agreements on international standards and regulations that apply to this industry.
- Explicit definition of target markets for hydrogen exports.

Another policy aspect central to all export policies concerns the position on domestic developments:

- Capacity building,
- Productive development,

27 Hydrogen Strategy for Canada, Seizing the Opportunities for Hydrogen, A Call to Action, https://www.nrcan.gc.ca/climate-change/the-hydrogen-strategy/23080.

28 Hydrogen roadmap, A Bet on Renewable Hydrogen, https://www.miteco.gob.es/es/ministerio/hoja-de-ruta-del-hidrogeno-renovable.aspx

In addition, it is relevant to understand the geopolitical change that the world will undergo as a consequence of the decrease in the consumption of fossil fuels (Kober et al., 2020).

3.4.8. Hydrogen transport by sea

Beyond the production process, the challenges associated with the maritime transport of H_2 are substantial and relevant to assess Chile's export potential. Nowadays, there are tanker ships that can transport LCO_2, and there is also a tanker designed and built to transport LH_2 cryogenically. This ship, called "*Suiso Frontier*", is part of the collaborative HYSTRA project[29] between Australia and Japan, and forms part of Australia's national green H_2 strategy (COAG Energy Council, 2019). Japan is committed to providing the technology for export, and Australia will produce brown H_2 thus establishing the complete value chain within the framework of its country strategies. The *Suiso Frontier* is in sea-trial, service and classification stages.[30] It has a cargo capacity of 1,500 m^3 for LH_2 at -253°C. Besides the propulsion system, the tanks are the most complex system to design and build on a ship of this type. Such a project aims to establish the feasibility of transporting LH_2 and thus scale up to larger capacity ships.

The construction of LH_2 ships requires conditions and capacities that the Chilean maritime industry does not have at the moment.[31] However, the *Suiso Frontier* can be regarded as a basis for a planning process to build this type of ship. The loading system of the ship is similar to current liquified natural gas (LNG) and chemical products loading systems. Aspects such as sloshing and the use of boil-off gases are gaps concerning green H_2, but applying the same principles as for LNG, it is feasible to solve in the short term (Ashworth, 2016; IMO, 2013).

Finally, the export of a fuel such as H_2 requires a thorough revision of protocols and responsibilities due to the inherent risk in its manipulation, which is justified and specified in codes such as the International Code of Safety for Ships using Gases or other Low flashpoint Fuels (IGF Code)[32] and the International Convention for the Prevention of Pollution from Ships (MARPOL).[33] The value chain of H_2 requires the alignment of politically driven regulations that will affect the geopolitical energy landscape. This type of dynamic results in member states adopting different positions towards new amendments or new regulations at IMO.

3.4.9. Hydrogen as a fuel for maritime transport

The IMO and the EU has been promoting the use of low-carbon fuels (European Commission et al., 2019; European Commission & EMSA, 2021; IMO, 2018), but such a process has significant challenges. For instance, the global availability of these fuels barely reached 2% in 2019 and is projected to reach 5% by 2025 (IEA, 2020a; IMO, 2018). H_2 as an energy source in interoceanic vessels is not viable due to significant differences in energy densities between H_2 and conventional fossil fuels such as HFO and MDO, which imply oversizing H_2 storage tanks by at least four times.[34] Even the *Suiso Frontier* consumes diesel as its primary energy source. The current energy conversion systems onboard tanker ships are thermal machines working under combustion processes that generate GHGs and pollutants (Woud & Stapersma, 2002). Even if green H_2 were to be used in the current propulsion and auxiliary systems, CO_2 emissions would be eliminated, but NOx emissions would remain (Nakagawa et al., 2012).

Some consideration has been given to applying fuel cells to replace current thermal engines in propulsion systems. This technology has been applied in smaller vessels (IEA - HEV TCP, 2019; IEA, 2019). However, the power achieved by H_2 fuel cell stacks reaches 6 MW to date (Corvus Energy, 2021), which is not enough to fulfil the operational requirements of interoceanic navigation (Molland, 2008; Molland et al., 2017). In consequence, the decarbonization process of maritime transport will likely occur in a transitional process using carbon-neutral fuels first –such as e-methanol and e-ammonia– and possibly fuel cells in the long run. This topic will be developed further in section 3.5.

Regarding the operation of cargo ships, and more specifically, tanker ships, there is a significant gap in personnel that has not been solved at the national and international levels.[35] Some institutions in Chile are forming officials and specialized crew members but competencies related to the manipulation of H_2 as cargo or fuel have not been included in the curricula until recently. Since there are no H_2 vessels available for training personnel, the aim would be to achieve a higher degree of specialization in LNG and other tankers. Such a program would require further alliances between universities and shipping companies. Even in such a case, the technological change from a matrix based on fossil fuels to H_2 is likely to cause resistance as the new onboard power technology requires a high degree of knowledge and expertise.

29 http://www.hystra.or.jp/en/.
30 https://www.classnk.or.jp/hp/en/hp_news.aspx?id=6124&type=press_release&layout=1.
31 http://asenav.cl.previewc75.carrierzone.com/es/barcos/; https://www.asmar.cl/en/.
32 https://www.imo.org/en/OurWork/Safety/Pages/IGF-Code.aspx.
33 https://www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/Marpol.aspx.
34 https://maritimecyprus.com/wp-content/uploads/2021/06/ABS-hydrogen-as-marine-fuel.pdf.
35 https://www.ics-shipping.org/press-release/new-bimco-ics-seafarer-workforce-report-warns-of-serious-potential-officer-shortage/; https://www.salmonexpert.cl/article/autoridad-martima-inicia-indita-mesa-de-trabajo-por-dficit-de-dotaciones/; https://www.bimco.org/news/priority-news/20160517_bimco_manpower_report.

3.5. Hydrogen derivatives and other value-added products

3.5.1. General description

Hydrogen can be used directly as a fuel or undergo further treatments to produce a wider range of products, such as synthetic fuels and chemical feedstock that can add value to the exports of renewable energies. Fuels can be produced and processed to a gas or liquid state and exported by ship or injected into gas pipelines. One way to obtain fuels is methanation, a process where H_2 and CO_2 –which can be captured from the atmosphere based on RE– is converted to synthetic methane (CH_4, natural gas, or SNG), and then, by liquefaction, made into LNG.

A second route for obtaining fuels is the Fischer-Tropsch (FT) process which converts CO_2 and H_2, through a series of chemical reactions, into synthetic crude, which is refined into various liquid hydrocarbons: diesel, gasoline, jet fuel, and naphtha (Ram et al., 2020).

Chemical feedstocks that can be produced based on hydrogen are methanol and ammonia. Synthetic methanol is obtained by combining H_2 and carbon oxides (CO), producing methanol and other chemicals. Moreover, H_2 can be coupled with dinitrogen (N_2) for the production of ammonia, an important feedstock for the chemical industry that is mainly used in agriculture as a fertilizer. Ammonia is also projected to be used, the same as methanol, as a fuel in vessels (El Mrabet & Berrada, 2021). Methanation, FT, methanol, and ammonia production are existing processes that need adaptations to work with RE supplies. This is the case of the High Innovative Fuels[36] (HIF) project located in the Magallanes region, which will produce e-fuels based on green H_2.

Chile has been identified as one of the countries with the best sites (Atacama Desert and Patagonia) in the world for sustainable fuels and chemical products based on hybrid PV-wind power plants, such as liquids fuels (Fasihi et al., 2016), synthetic methanol and dimethyl ether (Fasihi & Breyer, 2017) and ammonia (Fasihi et al., 2021). According to (Fasihi et al., 2016), the RE-PtL value chain needs to be located at the best complementing solar and wind sites in the world combined with a de-risking strategy, and a special focus on mid to long-term electrolyser and H_2tL efficiency improvements. In any case, the role of H_2 storage for the eventual export of its derivatives would be key to providing a more stable supply during the year, when the renewable electricity generation based on solar PV and wind power decreases in some seasons.

Existing internal combustion engines designed to use diesel or gasoline can be optimized to work with H_2 derivatives –such as ethanol-gasoline blends– without further modifications to the engine or vehicle. This feature implies that existing maritime and road transportation vehicles could use such blends (Verhelst et al., 2019). Efficiency and environmental performance depend critically on the technological solution. For example, conventional diesel accepts up to 10% blending with hydrogen; consequently, it would not effectively transform energy.

3.5.2. Environmental topics

Hydrogenation of CO_2 outperforms conventional petroleum-based fuels by reducing GHG emissions by 82.86% and reducing fossil fuel depletion by 82-91% (Matzen & Demirel, 2016). The use of fermentation-based CO_2 and wind or solar-powered water electrolysis for H2 production presents a sustainable and environmentally friendly way to produce transportation fuels.

Direct production of methanol from biomass (sugarcane bagasse) presents negative GWP values (-2,3 kgCO_2eq/kg Methanol), and its acidification potential is 7.9 gCO_2eq/kg Methanol (Renó et al., 2011). Once again, biomass methods yield large acidification potentials due to the intensive consumption of fertilizers in biomass cultivation and transportation. We must note that methanol gasification synthesis also produces pollutants like ash and tar, impacting human toxicity and eutrophication potential.

Green ammonia can be produced from hydrogen using renewable energy sources through the Haber-Bosch process. Currently, the most widespread feedstock for generating ammonia is hydrogen from natural gas steam reforming. Using fossil fuels simultaneously as feedstock and energy input to obtain ammonia presents substantial emissions. By replacing the methane-fed process with hydrogen produced by water splitting using renewable electricity, the CO_2 emissions could be significantly decreased in the Haber-Bosch process: from 1.5 to 0.38 tCO_2eq/tNH3 (Smith et al., 2020). The shift from intensive CO_2 methane-based ammonia production to green ammonia could significantly improve energy efficiency and eliminate direct CO_2 emissions (Fúnez Guerra, Reyes-Bozo, Vyhmeister, Jaén Caparrós, Salazar, & Clemente-Jul, 2020). Although the indiscriminate use of ammonia-based fertilizers and emissions of nitrogen oxides could disrupt the global nitrogen cycle if not addressed properly (Rockström et al., 2009).

Another important mitigation pathway of GHG is the production of common hydrocarbon fuels from renewable energy sources and carbon dioxide using the FT process. Large-scale FT plants outperform fossil diesel in all environmental impacts across all the designs, except for GWP, and ozone depletion, for which fossil diesel is a better option in some cases. This enormous variance

36 https://www.hif.cl/#Lanzamiento.

in GWP notes the importance of optimizing FT plants to reduce emissions from FT fuels. In the best case, the GWP of FT fuels could be 70% below that of fossil diesel (Cuéllar-Franca et al., 2019). Highly optimized FT fuels production could reduce the overall dependence on fossil resources and help climate change mitigation.

3.5.3. Economic topics

As mentioned above, the Atacama Desert and Patagonia are among the best complementing sites in the world for the production of sustainable fuels and chemical compounds based on hybrid PV-wind power plants, so the production cost of these items would be very low.

According to Fasihi et al. (2016), RE-diesel value chains are competitive for crude oil prices within a minimum price range of about 79–135 USD/barrel (0.44–0.75 €/l of diesel production cost), depending on the chosen specific value chain and assumptions for cost of capital, available oxygen sales, and CO_2 emission costs. These authors highlight that a sensitivity analysis indicates that the RE-based liquids fuels value chain needs to be located at best complementing solar and wind sites in the world combined with a de-risking strategy and a special focus on mid to long-term electrolyser and H_2-to-liquids efficiency improvements.

In 2030, with a 7% WACC, the cheapest RE-methanol and RE-dimethyl ether can be produced in Atacama and Patagonia with a price in the range of 400–500 €/t and 590–750 €/t, respectively (Fasihi & Breyer, 2017).

Ammonia-based on green hydrogen could be produced at the best sites in the world, such as Atacama desert and Patagonia, for a cost range of 440–630, 345–420, 300–330 and 260–290 €/tNH_3 in 2020, 2030, 2040 and 2050, respectively, for a 7% WACC (Fasihi et al., 2021). Comparing this to the decade-average fossil-based ammonia cost of 300–350 €/t, green ammonia could become cost-competitive from 2030 onwards.

3.5.4. Maritime transportation and use of hydrogen derivatives

As mentioned in section 3.4, while several organisms are promoting the transition to low-carbon fuels in maritime transport, the use of H_2 as the main fuel faces technological, training and institutional challenges that are difficult to sort out in the short term. On the other hand, most of the issues associated with hydrogen-derived fuels can be sorted out in the near future.

By contrast to H_2, the marine transport of fuels and chemicals such as LNG, liquid hydrocarbons, methanol, and ammonia is a mature technological issue and has a presence in Chile. The vessels that allow the transport of these fuels and chemicals have a capacity range of between 1,500 m^3 and 350,000 m^3 of liquid bulk cargo.[37] Existing dual-fuel engines can consume both liquid and gaseous fuels (Gomes Antunes et al., 2012; MAN B&W Engines, 2014), so it is expected that these ships will increasingly incorporate the use of green H_2 derivatives to power themselves (Ram et al., 2020). Some leading companies have already declared that their new vessels will use these fuels (e.g., MAERSK).[38] In addition, crew members could handle the technological transition towards these fuels more easily than in the case of H_2.

In conclusion, the decarbonization of maritime transportation will likely take a path where hydrogen-derived products will become valuable fuel worldwide. In such a scenario, port infrastructure would require adaptations and staff training to make these fuels available in different national ports and terminals.

3.6. Local productive development

3.6.1. General description

Clean energy could improve the export conditions of key products from Chile, thus promoting a new cleaner export sector, in line with the developed world's increasing concern with global warming. First, by reducing the associated carbon footprint and being more attractive to consumers who care about their choice's environmental impacts. Access to cheaper financial conditions for sustainable projects would be another advantage. Finally, cleaner products would avoid regulations by developed countries promoting low carbon economies and avoiding carbon leakage. The proposal of a border adjustment mechanism, a "carbon tariff," that could be charged to products with a significant carbon footprint is currently on the table. For example, producing copper based on a RE electrical matrix and green hydrogen in mining vehicles could allow an export premium on copper prices or increase the country's share in export markets that value this characteristic, as currently being observed for aluminium (Saevarsdottir et al., 2021; Tully & Winer, 2013). Similarly, the steel industry could use green hydrogen to reduce the iron ore (instead of following the current approach of using coal to produce coke, which is then used in the process) (Roland Berger GmbH, 2020). It would also allow avoiding possible carbon tariffs and access to lower capital costs. There are efforts to make Chile a vital food producer glob-

37 World Fleet Register https://www.clarksons.net/wfr/.
38 https://www.maersk.com/news/articles/2021/07/01/container-fueled-by-carbon-neutral-methanol.

ally, a role that needs to be strengthened by incorporating clean energies in the production of ammonia and fertilizers, hydrogen generators for farming equipment, and the use of diesel-hydrogen fuels or fuel-cell vehicles.[39] This would also allow lowering the carbon footprint of these products and avoiding a potential carbon tariff.

3.6.2. Economic topics

The access to international climate finance in Chile is reduced and restricted. However, it is possible to raise financing funds for the production of H_2 through a strategy of Blended Finance[40] in which a guarantee, placed in an escrow account, coupled with technical assistance can replace insurance, thus enabling the participation of a commercial debt provider in the project.

Financial instruments are required to support the investment cost stage (CAPEX) until competitiveness is achieved. In addition, the demand for green H_2 should be encouraged, and clear targets for the use of H_2 should be established to provide certainty to investors about the potential of this market. However, the financial instruments and regulations to promote H_2 demand and investment should be carefully designed to avoid transferring the investment risk to the State. Private investors should bear this risk and adequately incorporate it into their expected return rate.

3.6.3. Institutional-legal topics

Chile's Hydrogen strategy suggests some relevant institutional issues that need to be addressed. To accelerate the adoption of hydrogen in mining and the transport sector, it is necessary to define specific barriers and actions to be carried out. For this, a Public-Private Agreement for Hydrogen in Mining and Transportation, alongside essential public and private stakeholders, is required. It is also necessary to exchange experiences and formulate collaborative initiatives to bolster the green hydrogen use in Chile through bilateral and multilateral agreements.

3.7. Production of knowledge and capacity building

3.7.1. General description

The production of knowledge and the generation of capacities to produce renewable energies can be an export area by itself. As a country, Chile has the excellent opportunity to export knowledge concerning the technological adoption necessary to operate a highly renewable (variable) electricity system. Pushed by a progressive coal phase-out and significant insertion of REs the country can transform itself into a "natural laboratory" on how to approach highly renewable electricity systems with low emission levels, production of green hydrogen, power electronics, demand management, digitalization, etc., thus becoming an example of the energy transition. Such a demonstrative effect would yield lessons that translate into systematized knowledge.

Moreover, Chile has important strengths as an international player as an exporter of knowledge, research, development, and professional training in several disciplines and public policies. These strengths include a long history in solar energy as documented in (see Osses et al., 2019 and section 1.2), experiences in a wide variety of renewable energies (ACERA AG, 2021), different geographical and climatic conditions, with two pioneering plants in South America, such as Cerro Pabellón and Cerro Dominador.

Accordingly, Chile requires a solid base of local capacities to become an internationally recognized centre for producing knowledge and innovation that could offer services and training in RE. According to the seminal work of Cohen and Levinthal (1994), technological and production capacities at the local level are essential to interact with external sources of knowledge and technology, which allows expanding the possibilities of production and its benefits. Becoming an international player, recognized for its capabilities in the area, requires a balance between openness to foreign technology and interactive and dynamic local capabilities. If this balance does not occur, what international experience shows is that countries that depend mainly on foreign investment tend to develop enclaves that do not interact with the national innovation system. In cases of closure to external technologies, the updating or technological catching-up processes are too slow to achieve a competitive cutting edge (Aistleitner et al., 2021; Aridi et al., 2021; Freeman, 2006; Radosevic, 2022).

The production of knowledge and the creation of capacities for generating and exporting renewable energies requires public policies that promote the development of the formal education system in REs and the generation of dynamic and interactive productive capacities. Knowledge production should involve the identification of gaps along the supply chain of this type of technology, especially in those processes in which support services can be provided within the national territory. As an importer, Chile is the final destination of technologies. However, capacities related to support services, remanufacturing, reconditioning, reuse and maintenance of parts and equipment, and recycling processes can also be exported (Saavedra M. et al., 2018). Such capabilities are coupled with considerations in reducing their environmental impact and moving towards a circular economy (see section 4.5).

3.7.2. Educational policy for renewable energies

39 https://www.qff.org.au/blog/energy-savers-hydrogen-webinar/.
40 https://www.oecd.org/dac/financing-sustainable-development/blended-finance-principles/.

A primary condition for developing the production and export of renewable energies in the long term is to have public policies for formal education, reinforcing training at all levels and in a decentralized manner, and policies to achieve developing dynamic and interactive capabilities.

Pillar 4 of Chile's Energy Policy (Ministerio de Energía, Gobierno de Chile, 2015) explicitly states that energy education is an essential component for the development of our country. Promoting an energy culture in all sectors of society –including producers and users– will allow citizens to know and value energy. However, it is not enough to correct information and knowledge asymmetries; it is also required to generate knowledge, develop capacities, align interests and objectives in a shared vision of the development of the country and the energy sector by the year 2050.

The Ministry of Energy of Chile created the Energy Education Strategy[41] to promote public policy efforts to articulate and link energy and society. This strategy covers three areas. First, citizen training, which seeks to facilitate and promote access to information, resources, dissemination, and energy content for all citizens. Second, educational communities are meant to promote the good use of energy, educational resources, competitions, dissemination, and technical assistance from kindergarten to secondary education. The third area is human resources, which aims to promote the development of skills and training, specialization, and scholarships for sustainable energy management. Within this field, the initiative called "More human capital in energy" stands out. The initiative aims to promote the role of industry and academia in providing the foundations for the operative, technical and professional human capital that the energy industry requires. In this context, the Minister of Energy has indicated: "*human capital emerges as a key factor to achieve a successful energy transition and a sustainable energy future. Human capital is essential; we must train operators, technicians and professionals prepared to address the present and future challenges of our energy sector*".[42] In this sense, Chile has a robust and competitive Higher Education System that should be strengthened, directing its efforts and generating synergies, not only for training professional and technical personnel, but mainly for the formation of advanced human capital and interdisciplinary and inter-institutional university centres for research and innovation in renewable energies, energy transition and related fields.

For Chile to become an exemplary development model as a producer and exporter of renewable energies, applied research in production processes will be key, developing pilot experiences that allow training national professionals and technicians, expanding opportunities for jobs that are covered by the local workforce. It will also be necessary to create education and training programs around the production, storage, distribution, and use of green hydrogen, mainly for energy purposes.[43]

In relation to advanced human resources, there are 18000 male and female doctors, of which 61% graduated in the last ten years. However, Chile has 1.1 professionals dedicated to R&D activities for every thousand workers. In OECD countries, this figure reaches 8.3. In this sense, the Ministry of Science Technology Knowledge and Innovation maintains that "*among the main challenges, we still need to grow and become a leader in specific areas of knowledge. In addition, promoting doctoral programs in strategic areas; complement and strengthen the academic cloisters of the universities, including experts in areas related to technology transfer, innovation, public policies, and many others; attract more international students to be trained in our classrooms; strengthen the different mechanisms for the internationalization of these programs* (*internships, co-tutorials, attracting international experts to teach courses*)*; and encourage higher education institutions to articulate through consortia or other forms with different actors –public, private and academia– to generate more complex and higher quality doctoral programs, taking advantage of the research capacities of the different institutions* [...] *the foregoing will support the process of greater diversification of the trajectories of researchers beyond the academy, a necessary condition to achieve a growth of the ecosystem of science, technology, knowledge, and innovation.*"[44] These statements are perfectly in line with the proposal to position Chile as a benchmark in knowledge training, capacity building, and training in RE.

The implementation component in Chile's NDC has been grouped into three subcomponents, namely IM1 to IM3 (MMA, 2020). Two subcomponents are directly relevant for the current topic: IM1) capacity building and strengthening; IM2) development and transfer of technologies. The first of these measures is intended to promote the generation of technical capacities at the sectoral, national, and sub-national levels, to strengthen resilience in the face of the effects of climate change, and to promote the just transition of the workforce towards resilient development and low emissions. It also includes promoting research and the training of advanced human capital in areas related to climate change. The second measure contemplates that Chile will have the promotion mechanisms and instruments to focus and articulate the development and technology transfer processes for climate change in research centres, public technical institutes, centres of international excellence, and the training of the necessary human capital (Gobierno de Chile, 2020). These contributions, aimed at climate change, are directly linked to educational policies and capacity building in renewable energies, so there must be a close link between these processes.

41 Ministerio de Energía, Gob. de Chile, education strategy webpage, https://www.mienergia.cl/estrategia-educativa.

42 Revista Electricidad, https://www.revistaei.cl/2021/08/09/mesa-capital-humano-en-energia-se-han-realizado-mas-de-7-500-capacitaciones-en-energia-desde-2018/#.

43 https://www.ciperchile.cl/2021/05/29/hidrogeno-verde-en-chile-la-gran-oportunidad-para-crear-un-modelo-de-desarrollo-ejemplar/.

44 https://www.latercera.com/laboratoriodecontenidos/noticia/doctorados-capital-humano-avanzado-crece-61-en-la-ultima-decada/7MIPVKAKNJF6FK3FCY4SP72VWY/.

It is the role of the Ministry of Science, Technology, Knowledge, and Innovation to develop the Technology Development and Transfer Strategy for Climate Change, as stated in the project for the FLCC. This strategy should be closely articulated with the Energy Education Strategy and prioritize the RE sector.

3.7.3. Development of dynamic and interactive capacities

The innovation system related to the production and export of RE needs to develop dynamic and interactive capacities to achieve and maintain competitiveness over time. Such capacities are born and maintained through the relationship between public and private organizations, between companies and the local research and development network, and through the interaction with foreign technology sources and access to national and international markets (von Tunzelmann & Wang, 2007). The Innovation System is based on the synergies between different actors: private and public companies, universities, institutes, and technical training centres, state institutions, the financial system, etc. (Malerba, 1992). The development of competitive capabilities is possible when external knowledge sources are complemented with the local capacity to accumulate technology (Radosevic, 2022; von Tunzelmann, 2004).

The production of REs, as well as the activities to use and export them are located in the national territory, modifying social, economic and environmental life, with implications for justice and equity (Sovacool & Dworkin, 2015). The just transition is one of the demands of civil society in Chile and in Latin America (Transición Justa Latinoamericana, 2021) and the social pillar of Chile's NDCs, therefore a guideline for climate policy.

Production transforms resources into products or services by articulating different inputs and the use of technology, the so-called production function. One way to understand this relationship is through capacity building. The perspective of productive capacities distinguishes a first level related to the access to resources that productive actors have; a second level associated with the possibilities these actors have to transform or consume those resources; and finally a third level that is related to the profits or benefits that productive actors can obtain from these former transformations (von Tunzelmann, 2009). In this model, final or "downstream" producers offer their goods or services to consumers (in the domestic or export market), and in turn, demand different resources and inputs, including technologies and competent personnel from other "upstream" producers. In this sense, the demand for technologies and production capacities are derived from productive activity itself. On the supply side, the products that can be offered to the final consumer depend on the capabilities of the producers upstream and downstream. Each producer is able to transform resources and obtain benefits, which depend on particular levels of efficiency. The benefits are achieved only if there are consumers capable of obtaining a marginal utility for the product or service at the price offered.

The capacities to produce and commercialize, as well as those to offer technological services for production, and also the capacities to consume efficiently are dynamic and interactive (von Tunzelmann, 2009). This means that they are relational attributes, which are developed in the practice of doing and exchanging in a particular sector –in this case that of REs– in a specific territory and under particular historical circumstances. Technological and production capacities are essential for an "absorption capacity" to exist (Cohen & Levinthal, 1994), which is a condition for expanding production possibilities and their benefits. This "absorption capacity" needs to be involved through the whole supply chain.

REs are an emerging sector in Chile. The development of a world class innovation system in this sector depends on the balance between domestic technological capabilities –which provides autonomy– and the transfer of international technology –which opens up the system. Without balance, the benefits in productivity and technological updating of the industry are not achieved, as in the processes of integration of the countries in Eastern Europe into the global economy (Radosevic, 2022).

The achievement of world class interactive, dynamic capabilities needs guidance from public policy, for it will not happen spontaneously (Freeman & Soete, 1997). Public policy should aim at providing the conditions for the development of a network of actors, including public and private companies, educational institutions and academia, interacting to build strong production capabilities. The balance of local research and development and foreign technological upgrades needs to be assured and that implies funding for local experimentation and learning.

4. Cross-cutting issues

As mentioned before, some of the matters addressed in this report are cross-cutting to the value chain of energy production, either from solar, wind, biomass, hydro or other sources; for local consumption or export; or transmitted through transmission lines or ships. Therefore, these aspects are discussed in this section.

4.1. Paris Agreement Art. 6

It is important to point out that, in our best knowledge, there are no academic studies specifically focused on the implications of Art. 6 for Chile. The export potential literature has analysed specific exporting scenarios either for H_2 and its derivatives (Armijo

& Philibert, 2020; Gallardo et al., 2021; Hydrogen Import Coalition, 2021) or for electricity (Agostini et al., 2019; BID, 2017; Blanco, 2021; Sauma et al., 2011), but has not inquired about the relation between RE exports and Art. 6 in Chile. Nevertheless, based on the context described in the previous sections, the following views regarding the impact of Art. 6 emerged during the analysis phase of this topic:

- ITMOs that may be generated through export activities can hinder the fulfilment of the national goals established in the NDC, including environmental and social goals, if no provisions for robust accounting and for avoiding overselling of ITMOs are applied.
- Export initiatives articulated through ITMOs are an enabling mechanism to meet the national goals of the NDC.
- Art. 6 is key to creating a platform to boost Latin America's position as a region that exports its RE to the rest of the world.

The following is an analysis of these views in order to devise a common vision in this regard.

As it allows for international trades of mitigation outcomes (MO) and its use for compliance or other purposes, Art. 6.2 (cooperative approaches) has caught the attention of a myriad of stakeholders, including Parties at COP, multilateral agencies and NGOs. There will be a great deal of international oversight to ensure that it is used correctly and that no further emissions are generated as a consequence of its application. Several Art. 6.2 piloting initiatives are underway, pending the adoption of the rules, modalities and procedures of the full article, which is expected to occur at COP26. The main concern during the multilateral ongoing negotiations is how to avoid double counting of an ITMO, and how Parties are going to be held accountable for, because national emissions are increasingly under Party responsibility, hence there is caution on sharing MOs due to impacts on NDC. Mitigation outcomes cannot be used twice, and the tracking system should prevent this from happening. The parties will have to report if they have participated in international trades and used these certificates for compliance or other purposes. Thus, defining accounting rules is key. When it comes to the definition of an ITMO, it is still an open question. Offsets, emission allowances, and green and white certificates could be part of the menu, though there is no clarity up to date. In terms of metrics, it could be expressed in different manners, for instance, in tons of CO_2eq, in MWh generated by RE or in other metrics that parties may freely choose. The issue is how to make these metrics comparable and credible at the time of reporting. Chile is progressing in that regard, aware of the importance of having a system capable of tracking the MWh of renewable energy generated, especially if there is interest in trading them through different, independent standards. There is the need to have one trading platform that provides robust traceability and certainty of the environmental integrity of these operations, avoiding double use or double issuance of renewable energy certificates. For that purpose, the National Electric Coordinator (independent system operator) is implementing the National Renewable Energy Registry (RENOVA)[45] which allows for the traceability of every MWh, from its generation point to its consumption based on the bilateral contracts. Using blockchain technology, it can identify and track the electricity generated by renewable energy with a high degree of security, thus avoiding double-counting of the green attribute.

We are certain that for Chile and its energy transition, Art. 6 could enable an increase in ambition over time by granting access to emission reductions that are currently above our feasible national efforts, or by advancing the implementation of current measures and technologies that today have a high cost and are far from the cost-effectiveness principle that is currently contemplated in the package of measures to achieve Chile's NDC. The focus on the fulfilment of the NDC could be the first target in the strategy, with Article 6 being functional to this means, and should also support socially fair and just transition and climate justice (Ikeme, 2003). This is a critical element of the strategy (Chile's NDC) because this implies the decarbonisation of the power sector which in turn triggers transformational changes in other relevant sectors such as industry, transport and housing, enabling, for instance, e-mobility and green hydrogen as relevant mitigation measures, thus contributing to overall emissions reduction to 2050. Consequently, an export strategy would allow linking the implementation of pledges in the NDC with Chile's Long Term Climate Strategy and the Global Stocktake as a monitoring system of overarching goals of the Paris Agreement (Vandyck et al., 2016).

An additional element to consider is that the export strategy may result in additional emissions and environmental impacts from the construction and operation of the new needed infrastructure and equipment. This should also be considered in the analysis.

In this scenario, carbon pricing (and Art. 6 in particular), can be an essential part of sound climate action in the country and in Latin America, as it is the most cost-effective policy tool for emissions reduction because it promotes the implementation of low cost reductions, it has the potential to spur cooperation among Parties and, if the price is high enough, it can properly internalize the costs of carbon by fostering transformational changes in industry and the economy for good.[46] However, their effectiveness in driving long-term investments depends on allowance prices and trust and confidence in the policy. Therefore, an exporting RE strategy must be structured thinking in the adequation of already ongoing investments and the new ones, post COP26.

45 https://www.revistaei.cl/2021/05/27/plataforma-renova-del-coordinador-electrico-nacional-permitira-certificar-produccion-de-hidrogeno-verde/.

46 Based on the World Bank CPLC 2021 Report of the Task Force on Net Zero and Carbon Pricing. https://www.carbonpricingleadership.org/netzero.

This is particularly true for hydrogen. Different countries, such as Australia, Brazil, Morocco, Spain, Portugal, Canada and Russia, consider themselves exporters of hydrogen and its derivatives. However, in general they do not provide quantitative production targets in their strategies or are building their design, which would allow them to know in what percentages they will meet this global demand. Hydrogen and hydrogen-based fuels are expected to replace 13% of global energy demand. According to IEA (2020b), the hydrogen market is around 75 million tonnes per year and will grow to 95 million tonnes by 2030. Therefore, if Chile reaches the 25 GW of electrolysis capacity by 2030 indicated in the National Strategy, it could produce 3 million tonnes of green hydrogen, representing 3% of global production by that year. Consequently, a global demand captured by other countries is not seen as a development barrier for Chile.

More concretely, Chile can export surplus energy today, under existing technical and regulatory conditions. In particular, solar power exports from Chile to Argentina would result in total benefits around US$47 million per year for both countries together, in addition to environmental and international cooperation benefits. On the other hand, Chile would currently benefit from importing natural gas from Peru at night, thus substituting diesel generation. In particular, the average daily marginal cost would be reduced by 43% with an annual benefit of US$10.5 million (Agostini et al., 2019). In the future, the production of SNG that could be obtained from green hydrogen in Chile can be evaluated as an alternative. The virtues of exporting short-term surpluses include the demonstration that RE exports are feasible, new investments are not required, and countries build a trust relationship that would allow to deepen the energy exchange in the future, thus reducing political barriers.

It is worth mentioning that to achieve the greatest local impact of hydrogen penetration, the development of technologies that make use of hydrogen is required. Many of them are in the pilot phase. Chile could participate early in these developments so that commercial solutions arrive, and the required ecosystems (O&M) are created earlier in our country.

Another aspect of an export strategy is related to regional integration (Latin America) as a clean energy exporting block (cluster) to the world. Latin America possesses considerable RE potential, which could play a key role in sustainable development on a global scale. The report by Moreno et al. (2020) extends the integrated economic and climate assessment model proposed in the literature to study the export potential and global impact of RE from Latin America and the Asia-Pacific region. Predictions from extended model with the updated information show that: (i) the export of RE from Latin America and the Asia-Pacific region to the rest of the world generates economic benefits for all regions, but does not reduce the effects of global warming and, on the contrary, exacerbates the problem; (ii) if RE exports are accompanied by policy measures (e.g. carbon taxes) that discourage the use of polluting energy sources, it is possible to slow down global warming and, in turn, generate significant economic gains for all regions, in comparison to the situation without any such exports; (iii) while all regions benefit from RE exports, Latin America's economic gains can be above the global average; (iv) delaying the development of RE exports reduces economic gains not only during the delay period, but also in the years following the commencement of exports. The simulations and sensitivity analysis of tax levels and future uncertainties presented here enable us to assert that exports of RE from Latin America to other regions, together with policies that reduce carbon emissions, generate a virtuous circle that mitigates climate change. Such integration would allow coordinating the implementation of individual NDCs, sharing efforts and required support, resulting in a sort of Regionally Determined Contribution (RDC) that allows structuring the scope of the goals of each NDC in relation to time, but in a cooperative manner, i.e., advancing according to regional capacities and not only individual ones, beyond an individualistic or bilateral/multilateral transactional logic.

4.2. Export development implications on sociotechnical systems

In order to understand social implications from the development of exporting potential, we need to approach the complexity and interrelations among technical processes, human and economic resources, knowledge and cultural meanings. Energy-systems transformations are not disaggregated from social systems, so they shouldn't be seen as separate processes that affect each other, but as part of the same socio-technical regime (Geels, 2004, 2010; Geels et al., 2017). It is from the transformations in the conditions of a sociotechnical system that emerge new forms of interaction and new internal linkages between consumers, producers and regulatory instances and external interaction, through the infrastructure, with their relevant environment as political, legal, scientific, economic and ecological systems (RedPE, 2020; Valencia et al., 2021). Therefore, energy transitions not only imply technological changes for energy infrastructure, but inherently political processes which entail transformations in the social and cultural relations and structures, enabling to move towards more democratic and just models for energy development, but also enabling the strengthening of existing power relations (Avelino et al., 2016; Avelino & Rotmans, 2009; Avelino & Wittmayer, 2016; Boyer, 2014; Brand, 2016; Brand et al., 2020; Bues & Gailing, 2016; Burke & Stephens, 2018; Gailing, 2016; Hafner & Tagliapietra, 2020; Healy & Barry, 2017; Hendriks, 2009; Kenis et al., 2016; Köhler et al., 2019; Meadowcroft, 2009; Mitchell, 2013; Stirling, 2014; Szeman, 2014; Szulecki & Overland, 2020).

As a consequence of the above, there is a risk of increasing social unrest, if transformations of energy systems do not come along with early measures aimed at properly addressing implications in terms of justice and equity (Calvo et al., 2021). Implications as the accentuation of extractive dynamics of dispossession for decarbonisation are usually hidden in negotiations and actions for mitigation, but have been reported through the literature of energy social research (Agostini et al., 2017; Baker, 2015; Brock et al., 2021; Dunlap, 2017, 2020; Gudynas, 2020; Hernández, 2015; Hesketh, 2021; Kelly, 2019; Kelly-Richards et al., 2017; Keucheyan, 2018; Newell & Mulvaney, 2013; Ramirez & Böhm, 2021; D. N. Scott & Smith, 2017; Sovacool, 2021, 2021; Sovacool, Baker, et al., 2019; Sovacool et al., 2021; Sovacool, Hook, et al., 2019, 2019; Sovacool, Martiskainen, et al., 2020; Svampa & Viale, 2020; Yenneti et al., 2016). Under the cover of "the green discourse", this type of dynamics has sacrificed local sustainability for global sustainability and externalised risks, costs, and uncertainties at the expense of ecosystems, territories - often rural - and vulnerable social groups with limited power of participation and influence (Brock et al., 2021; Golubchikov & O'Sullivan, 2020; O'Sullivan et al., 2020; Sovacool, 2021; Sovacool, Hook, et al., 2020; Yenneti et al., 2016).

In that sense, it is necessary to note that two guiding principles are relevant to any RE development. There is a "Energy Justice" and a "territorial socio-ecological approach" (Calvo et al., 2021b).

Energy Justice as "a global energy system that fairly distributes benefits and costs of energy services and is based on fair and representative decisions" (Sovacool & Dworkin, 2015). According to Heffron (2018) moving towards a just energy system requires that decision making considers energy justice from its three principles: distributive principle (concerning the costs and benefits of production, transport and distribution processes and the provision of energy services) (Healy et al., 2019), procedural principle about decision-making procedures and their instances of participation), and restorative principle (about the recognition of territory and segments of society that have been historically affected or ignored by global energy development).

These principles operate on a multi-scale, spatial and temporal level, understanding that there are injustices upstream and downstream of the energy supply chain. These injustices are associated with the extraction, processing, transport, supply and disposal of energy production residues, whose impacts can be assessed at different locations and timescales.

Addressing these principles implies identifying the multiple effects that initiatives framed in decarbonisation and energy transition processes are having in terms of degradation, dispossession and destruction through the co-optation of resources and land, exclusion in planning, destruction of ecosystems, and the reinforcement of inequalities and vulnerabilities (Sovacool et al., 2021). Therefore, decisions such as promoting the country's export potential first require recognising possible tensions that emerge or are reinforced throughout the life cycle of energy production and supply processes. McCauley (2018) outlines the guiding questions in an intersection of the energy justice principles with the guidelines of the so-called "energy trilemma" that guide the energy transition policies (Availability, Accessibility, Sustainability), which are presented in Table 4.

Table 4
Energy trilemma
Source: McCauley (2018).

	Availability	Accessibility	Sustainability
Distributive principle	Where are resources located?	Where does energy consumption take place?	Where do emissions to the environment are produced?
Restorative principle	Who does not benefit from the resources?	Who cannot access it?	Who does not produce emissions to the environment?
Procedural principle	How are production decisions made?	How are consumption decisions made?	How long-term are structural policies?

A "territorial socio-ecological approach" means that the decision-making process must seek to contribute to mitigation, adaptation and training measures relevant to each territory's reality from a systemic perspective and recognizing the different social-ecological interrelations in that territory. Such an approach also includes that coordination must be promoted, focusing on the multi-scale relationships among other territories. That means favouring territorial land-use planning units that reflect the dynamics and limits of social-ecological systems (watersheds and airsheds, biodiversity zones, etc.) and transcending and coordinating the traditional administrative units (Billi et al., 2021).

To fulfil these approaches, it is necessary to analyse those aspects that may derive in particular tensions, given their relevance for the conditions of inequality and conflict in the country, which are detailed in the following subsections.

4.2.1. Development model and indigenous participation

The exponential incorporation of renewable energies –at least in the electricity matrix– has neither promoted local development in the territories where they are located nor the effective participation of communities in decision-making (Flores-Fernández, 2020; Furnaro, 2020). Initiatives such as the export potential of RE in its various forms –associated with mitigation negotiations and actions– will potentially impact the deepening of the extractive dynamics of dispossession for decarbonisation that has been widely documented/denounced by the social studies literature on energy (see section 4.2).

This situation is directly related to economies mainly based on the concept of "extractivism". In international literature, extractivism is understood as a multi-scale process that involves the mobilisation of large volumes of natural resources, generally unprocessed, and the specialisation of territories in mono production. Extractivism is based on the idea that natural resources exploitation will bring social and economic development. Still, evidence shows that investment projects are imposed in local spaces without adequate mechanisms for free and informed citizen participation, minimal compensation and mitigation schemes, and negative social, political, economic and especially environmental outcomes (Acosta, 2011; Gudynas, 2009; Svampa & Viale, 2014). A particularly negative feature of extractive dynamics is the emergence of "sacrifice zones" (García-Guadilla, 2009; Gudynas, 2009), segregated areas where human and non-human life is compromised in the name of national progress or economic growth (Valenzuela-Fuentes et al., 2021), and where job and entrepreneurial opportunities become less diverse, scarce and precarious, resulting in migration or poverty.

Local resistance to these imposed investment projects is transformed into a conflict against the state, which is understood as a distributor of socio-environmental injustices. The state's limited capacity to manage disputes causes their escalation territorially and politically, generating massive rejection because of the lack of democratic decisions related to the environment, the lack of clarity about the direct and cumulative benefits due to these projects, and the lack of knowledge about their future impacts in the short, medium, and long term (Acosta, 2011; Gudynas, 2009; Svampa & Viale, 2014).

In Chile, extractivism has been a particularly negative experience for indigenous peoples. In the north of the country, the Aymaras, Quechuas, Likan Antai or Atacameños, Collas, and Diaguitas have experienced direct impacts from large-scale copper, lithium, and gold mining. These impacts are reflected in the loss of sovereignty over the environment in which they live, resulting from the capture of water, the installation of infrastructure, mining camps, urban transformation, the collapse of roads, and air pollution. Also, these practices have significant disruption to traditional ways of life and local political leadership forms due to relations with the mining companies and local governments and the alteration of community relations as a result of clientelism (Bolados García, 2019; Bustos-Gallardo & Prieto, 2019; Romero-Toledo, 2019).

Similarly, in the south of the country, the Pehuenche in the mountain, the Mapuche in the valleys and the Huilliche in the Andean sectors have rejected the installation of large hydroelectric plants, but also run-of-river hydroelectric plants, both for cultural reasons within ethno-political processes, and because of the traumatic experience of ENDESA in the Alto Bío, which meant the displacement of people from ancestral lands, the flooding of sacred sites, and the urbanisation and impoverishment of the population.

The Mapuche of the valleys, among other issues, reject the mono production of forestry in the regions of Bío, La Araucanía, and Los Ríos, which has impacted on their territoriality, surrounding the Merced Titles where the Mapuche communities are located. According to the communities, these practices also affect the access and availability of water, increasing vulnerability to forest fires, among others. In practice, the forestry industry has not meant any development for Mapuche communities; on the contrary, it is the primary source of conflict in southern Chile (Hofflinger et al., 2021; Höhl, 2018; Latorre & Pedemonte, 2016; Richards, 2013). Finally, it is necessary to mention that the maritime territory of the Lafkenche is impacted by industrial fishing that uses the rivers for the breeding of fingerlings. In the extreme south of Chile, the Yaganes and Kawésqar reject the growth of salmon farming in waters of high cultural and environmental value, some of which are close to biosphere reserves.[47]

According to the Human Rights Institute, 38% of environmental conflicts are related to projects in the energy sector, which is also the sector with the highest level of conflict in Chile. 40% of energy sector conflicts occur in indigenous territories, and 11% are affected in the lowest quintile (INDH, 2021).[48] In this context, RE production must understand the history of conflict in the territories to avoid repeating the history of extractivism and its impact on local territories and communities. RE exports must first address the needs of local, indigenous, and non-indigenous communities and generate social and territorial cohesion. In this sense, the promotion of RE micro-projects in local communities respecting interculturality, even if they do not contribute to the export potential, would have the virtue of incorporating these communities in a fair and inclusive energy transition process, facilitating legitimization and support for large RE exporting projects, thus increasing global energy governance.

4.2.2. Just Transition

Some scholarly researchers have established a close link between the "climate justice" and "energy justice" analytical frameworks through the "just transition" concept (Carley & Konisky, 2020; García-García et al., 2020; Siciliano et al., 2021). Historically, the "just transition" concept has aligned workers' concerns about workplace health and safety, employment, livelihood, and quality job opportunities, with environmental preservation movements (Morena, 2018; Stevis et al., 2020). So, it is no surprise that the concept has taken significant importance in recent years, mainly due to the conjunction of the environmental and climate crises with situations of high levels of poverty, inequity, and social discrimination experienced by vast regions of the planet (García-García et al., 2020).

The concept has become part of the language of the current debates on climate change, and it is used by diverse groups of stakeholders, like international organizations, governments, NGO's, indigenous groups, feminists, philanthropists, and by the business sector as well. However, not all of them have the same idea about its meaning, or how, or whom it should be accomplished for, but most share the belief that the "just transition" concept involves that justice and equity considerations must be a substantial part of discussions and policy decisions about low carbon transition process (Morena, 2018; Stevis et al., 2020).

As some scholars have noted (Carley & Konisky, 2020; Lederer et al., 2018, 2019; Siciliano et al., 2021), this idea is consistent with the multiple goals for the energy transition process that have being expressed by the international community: providing clean energy access, greening the economy, creating better jobs, lowering poverty and inequity, while protecting the environment and tackling the climate change. This is also in line with the 2010 UNFCCC Conference of the Parties agreement that included the concept in the international negotiations: "*addressing climate change requires a paradigm shift towards building a low carbon society that offers substantial opportunities and ensures continued high growth and sustainable development, based on innovative technologies and more sustainable production and consumption and lifestyles, while ensuring a just transition of the workforce that creates decent work and quality jobs*" (UNFCCC, 2010).[49]

The main notion behind this conceptualization is based in the need that specific climate and energy policies will be required to prevent potential adverse consequences for communities and socioeconomic groups at the transition frontlines, likewise, reducing disparities in the distribution of the energy transition benefits and burdens (Carley & Konisky, 2020).

47 https://radiojgm.uchile.cl/comunidad-kaweskar-contra-salmoneras-tenemos-evidencia-de-desaparicion-de-especies-autoctonas/; https://observatorio.cl/declaraciones-de-comunidades-kaweskar-en-relacion-catastrofe-ambiental-producida-por-el-derrame-de-40000-litros-de-petroleo-al-mar/

48 https://mapaconflictos.indh.cl/#/.

49 English version: https://unfccc.int/sites/default/files/resource/docs/2010/cop16/eng/07a01.pdf; Spanish version: https://unfccc.int/sites/default/files/resource/docs/2010/cop16/spa/07a01s.pdf.

In Chile, both the Ministry of Energy and Ministry of Environment are working on a proposal for the Just and Sustainable Transition Strategy, whose goal is to ensure social and environmental development under a justice and equity framework. This goal includes the improvement of people's livelihood through "green" jobs, and environmental conditions enhancing on the territories where energy projects will be located.[50] This strategy is part of the Chilean NDC commitment (Gobierno de Chile, 2020).

At the moment, the main focus of the strategy has been situated on the closure of the 28 coal-fired power plants existing in the country. In light of previous analysis, several concerns open up with this process, specially related to economic, technical, and environmental aspects, social issues, and political implications as well. These concerns must be taken into account, in order for the strategy to accomplish with its declared purpose and the international commitments.

Recently in Chile, as part of a wave of Latin American debate on energy transition among civil society organisations, the decarbonisation of the energy matrix has been linked to the conceptual framework of just transition (Núñez, 2020; Soler, 2016; Transición Justa Latinoamericana, 2021). This discussion broadens the scope beyond the agenda set by the international trade union movement to address the impacts of energy projects that have not had sufficient institutional response: environmental and social conflicts, economic inequality, injustices, indigenous people, displacement of rural communities, air and water pollution, famines and epidemics (Soler, 2016; Transición Justa Latinoamericana, 2021).

In this debate, the question "energy for what and for whom?" arises, focusing on the risk of intensifying the "extractivist model" of the global south as applied to energy projects. It is also important to highlight the possible impacts of, for example, the increase in demand for critical metals required for the construction of the infrastructure necessary for the energy transition. Faced with these scenarios, the organisations propose the need to consider energy as a right and a common good, the achievement of policies for energy sovereignty (Soler, 2016; Transición Justa Latinoamericana, 2021) and a change of ownership, scales and power relations in the sector (Transición Justa Latinoamericana, 2021).

4.2.3. Energy Poverty

One of the main challenges in assessing the impacts of the energy system and the decisions to be taken regarding its future and export potential is to pay adequate attention to the transformation in configuration and dynamics of socio-technical systems at different spatial and temporal scales. Particularly at the household level, the concept of energy poverty has received special attention in recent years (Calvo et al., 2021). Energy poverty refers to the insufficient satisfaction of relevant energy needs, which must be understood within a specific territory and concerning particular standards. These energy needs can be of different kinds, but for this report, we will focus on those that are mainly linked to domestic uses and have a direct relation to the health, welfare and fundamental rights of the population (Urquiza et al., 2019).

Energy Poverty in Chile manifests itself through problems of great depth and urgency, such as the high concentration of particulate matter in the home, resulting in deaths and emergency care for critical episodes of respiratory diseases (Huneeus et al., 2020). Therefore, energy poverty is an urgent and unavoidable problem, and therefore decisions to transform the energy system cannot increase the existing gaps in inequitable access to quality energy. On the contrary, it must be one of the priorities focused on the design of public policies, which is also in line with the Sustainable Development Goals, particularly goal 7 (UN, 2021). Addressing this challenge within the framework of global efforts to transform the country into a clean energy exporter means never neglecting, in public policies and national and regional action strategies, the energy needs of local populations and particular territories.[51]

4.2.4. Co-creation Relevance

Community participation in large-scale energy projects in the country has been much more frequent in recent years. Including the active participation of the community in the planning stage of any energy project allows to identify, at an early stage, the community experience, knowledge and concerns of the project sitting. For example, in Ubilla et al. (2014) a methodology of community engagement has been proposed and used in a real-world project, where the community was involved from the planning to the operation stage. Indeed, communities are typically very much involved when they participate in the project operation (see Kanamori et al., 2013; Xiao et al., 2018). With this evidence, it seems important to foster the participation of the community in the decision process at the planning stage with a co-construction process (e.g. Montedonico et al., 2018).

As mentioned in Palma-Behnke, et al. (2019) a co-construction process is understood as a technology transfer process that occurs in a sociotechnical system. It is possible to distinguish three levels: 1) the technology and infrastructure that compose the application, 2) the social structure that manages the technology through a previous established model, and 3) the relevant environment, which comprises the natural and socio-cultural environment, considering the local and regional political and organizational culture, the productive chain and the institutional frameworks, which will be affected by the impacts of technological and social innovation (Geels, 2010, 2019). It is relevant to understand technological innovations as a transdisciplinary process,

50 Estrategia de Transición Justa en Energía: https://energia.gob.cl/mini-sitio/estrategia-de-transicion-justa-en-energia.

51 Red de pobreza energética: http://redesvid.uchile.cl/pobreza-energetica/.

since it corresponds not only to a question of technological transformations but also to a cultural, social, political, economic and geographical challenge (Valencia et al. 2021). This process is understood as a dialogue of knowledge where different rationalities converge for the solution of a single problem (Tillmans & Schweizer-Ries, 2011). This dialogue seeks to achieve an effective participation of scientific and non-scientific actors and communities in the quest for sustainability of the solutions (i.e., export projects), highlighting the need for new participatory approaches to codesign and coproduction of solutions. In this way, sustainable energy transformations can be a process that not only involves technological changes, but also social, cultural and governance transformations.

4.3. Towards energy literacy

The social pillar of just transition and sustainable development in Chile's NDC is particularly focused on the decarbonization process of the electricity generation matrix. It indicates that the difficulties and needs of those who are particularly vulnerable should be analysed, recognizing, respecting and promoting the obligations related to a just transition towards a low-carbon and climate-resilient economy. In addition to fostering the knowledge and technology capacities mentioned previously, this just transition pillar also requires that there be an energy literacy environment extended to a large part of the population. Chile needs an energy literacy of the population about knowledge, affectivity and behavior (Martins et al., 2020) upon four typologies: device energy literacy; action energy literacy; financial energy literacy and multifaceted energy literacy (van den Broek, 2019). This issue is extremely relevant in terms of closing knowledge gaps that affect participation processes deeply (Höhl et al., 2021).

Despite the growing interest that energy literacy has produced among researchers, so far no consensus definition has been reached. DeWaters and Powers (2011) define energy literacy as mastering basic energy-related knowledge, along with understanding the impacts of energy production and consumption on the environment, how energy is used in daily life, and adoption of energy-saving behaviours. This definition adds three dimensions to the traditional concept of energy literacy: knowledge, attitude and behavior, which are not always considered, due to a narrower vision that focuses on the economic notion of cost-benefit (Martins et al., 2020). The US Department of Energy offers a broader view, stating that energy literacy encompasses not only the understanding of the nature and role of energy in the world and in everyday life, but also the ability to apply energy concepts and to understand how to answer questions and solve problems (U.S. Department of Energy, 2017).

Chile needs to achieve a sufficiently informed and educated population in energy issues, to participate in decisions about production and support expansion policies for its renewable energies. However, our biggest imbalance is inequality. A growth agenda cannot alone address the history of inequality, but must be addressed through higher quality growth, which requires quality education (Levens, 2014).

The massification of energy literacy is not, however, an easy goal to achieve given that a set of factors must be considered, among which are, from modifications in school curricula, to the effective incorporation of communities to RE technologies, including all types of environmental and energy education and including the massification, to the extent possible, of renewable energies for domestic use. Research indicates that mere formal education on the subject is not enough (Parker, 2020) but that real behavioural changes are achieved when pilot experiences are introduced that change daily habits and techniques in relation to the sustainable use and consumption of energy.

4.4. Innovation capacities for better governance

An appropriate balance between openness to imported, cutting-edge technologies and development of local capabilities is a key factor that allows countries to be at the technological forefront. In fact, a key factor for the acceptability of new productive activities in the territory and to its contribution to sustainability, is to avoid the creation of enclaves, i.e., an industry dominated by international or non-local capital that extracts or uses local resources or products, without linking to local capacities or benefitting the region. This situation has been seen in processes of different nature. For example, in the openings of Eastern European economies (Radosevic, 2022) and the unfolding of the oil industry in Mexico (De la Vega, 1999) and other countries in the 20th century.

A higher innovation capacity reduces the formation of enclaves with limited linkages to the development of local actors. The knowledge and skills developed in the industry and its suppliers allow the rapid creation and adoption of new technologies and the generation of additional added value. In Chile, the nationalization of copper followed a process that allowed reducing enclaves (Ibarra Mendoza, 2013; Urzua, 2013).

The governance analysis of the innovation processes required to develop RE production and export capacities is facilitated if their objectives are explicit. If these objectives are articulated as a mission, actor alignment and capacity development can be managed. A "mission" is a socially desirable objective that guides the coordination of social actors (Mazzucato, 2021). Currently, the production and export of renewable energies has not been approached concerning the solution of a relevant social problem for the country, including the state, the private sector, and the citizens.

Thus, the production and export of renewable energies should respond to a mission that solves a social problem, for example: "to achieve energy sovereignty with renewable sources and in the process of just transition". That could be a starting point for the participatory processes indispensable in determining a mission with social legitimacy.

The transformation dynamics of industrial sectors can be explained by the co-evolution of technological systems, the creation and adoption of new technologies, and governance (von Tunzelmann, 2003). The organisation of collective action depends on structural issues regarding how decisions are made and controlled, the power relations between actors, and the implementation and control of decisions taken. Among these structural aspects are institutions and legislation.

However, in terms of exports and the evolution of international markets, the analysis of Chile's potential position in the RE export market requires an analysis of global geopolitical scenarios and strategies. Therefore, topics beyond the scope of this section of internal institutional research remain in politics, given that it is a strategic market that is likely to be explained in this arena according to the trade agreements and international relations involved.

Chile is a marginal player in the energy market, dominated by great powers. But, of course, competition conditions will impose standards and capacity requirements to participate in the market, so the institutional and legislative analysis should consider the requirements as a condition for the study and development of the innovation system.

4.5. Circular Economy

In spite of the environmental benefits of RE in terms of GHG reductions, the transition towards a RE economy may have substantial environmental impacts (described in previous sections). In order to minimize further socio-environmental problems and conflicts, such a transition should be carried out as part of a broader transition towards a circular, minimum-waste economy. According to the European Parliament, "the circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value."[52]

Understanding the length of the logistics chains involved at the level of installations as well as the production of technologies is a key input to build a circular economy (Olabi, 2019). Today, the technologies and devices associated with the generation of RE plants are assembled from parts and pieces that were manufactured far from the destination sites. As the insertion of REs in the energy matrix grows over time, the materials from such facilities will accumulate, becoming waste at the end of their lifetime.

As in the case of multiple electronic products, Chile is the final destination of numerous technologies. Far from the original manufacturing sites, the recycling of parts and pieces, as well as the recovery of materials for their use in other industries, could be complex. The capacity and infrastructure for classification, separation, recovery and reconversion technologies is almost non-existent (UNEP, 2019). In the current scenario, the generation of industrial waste is a major environmental risk factor which must be addressed by the implementation of a logistic system to manage the undesired by-products of RE production.

The main challenges to move towards circularization come mainly from extending the life span of plants through reuse, repair, reconditioning or remanufacturing processes. These processes prevent the formation of waste but require the creation of capacities within the country that are not currently available.

Both the recovery of materials and the life extension processes open several opportunities for Chile, not only for new RE ventures, but also for the creation of services derived from the energy transition. Such considerations are valid not only for producing and exporting H_2 but also for the associated technologies, which involve storage systems such as fuel cells.

Finally, the LCA of both RE plants and hydrogen production is a crucial input for the design of circularization processes. The environmental impact assessment includes considerations beyond materials in their final disposal, i.e., the use of other ecosystem services such as water and soil use; the impact on flora, fauna and objects of national interest; and aspects associated with citizen participation; as well as the impacts of possible hydrogen leaks and hazards in the handling and transport of hydrogen.

The circular economy generates a framework to conceptualize this industry throughout its supply chain, its socio-environmental impacts as well as the opportunities to be developed within the national territory, both for the extension of the life span of plants and for the recovery of materials. The transition towards industrial processes that favour the installation of a circular economy in a transition to clean energies leads to the reduction of emissions along the production chain (Su & Urban, 2021).

52 https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits.

4.6. Economic efficiency and instruments for renewable energy exports

From the perspective of mainstream economic theory, three types of efficiencies are of interest in making optimal use of a society's resources, in which there are multiple competing, alternative uses:

- Allocative efficiency, which means allocating resources in the economy to the most valuable uses for society among all possible uses. This feature requires that the prices of goods and services correctly reflect the private and social costs of producing them. However, it can be possible only if free competition exists and information asymmetries and externalities are absent. The latter is a critical issue in the case of environmental and socio-cultural impacts.
- Productive efficiency which consists of producing goods and services at the lowest possible cost, taking into account economies of scale (the unit cost of production decreases with the volume of production) and scope (the cost of producing two goods together is lower than making them separately). To make this applicable, one of the requirements is that public policies must be technology-neutral. In particular, it is always inefficient to affect the production function of a good or service. Instead, what is relevant is to get the correct input prices, which implies taxing inputs to those that its uses generate negative externalities and letting each company decide on its optimal mix of inputs and technologies in a competitive market. In the case of new emerging markets, such as the export of renewable energies, the State could play a key role as an articulator (McCloskey & Mingardi, 2020; Freeman & Soete, 1997; Mazzucato, 2021). This aspect shows the complexity of reconciling economic efficiency objectives with the creation of new markets.
- Dynamic efficiency, which consists of having the right incentives for investment and innovation over time. Promoting this dynamism may, in addition, include other public policies (such as systems of innovation, education, among others) complementary to investment incentives (Bourdieu, 1986; Mazzucato, 2021 ; McCloskey & Mingardi, 2020).

Theory and evidence suggest that good economic institutions are a relevant explanation for growth, development, and prosperity in countries (Acemoglu et al., 2004). The consensus so far is that adequate institutions refer to clear and respected rules of the game, particularly concerning property rights and the existence of competitive markets (Acemoglu et al., 2005, 2017; Acemoglu & Robinson, 2019; Parente & Prescott, 2000).

First, property rights play the role of generating incentives to invest in physical capital and technology, as well as in human capital. On the other hand, the existence of competitive markets allows an efficient allocation of resources. The economic measures and public policies adopted for energy exports must consider an institutional framework that clearly establishes the rules of the game, in particular, property rights and free competition in the markets (or appropriate regulation when competitive markets are not possible).

In addition, the right incentives must be generated simultaneously, both in terms of investment and innovation, so policy must consider both allocative and productive efficiency criteria, which means that taxes should be set to correct negative externalities and subsidies should be provided only in cases where there are positive externalities.

4.7. Market Integration

Following the discussion in Section 4.1, the synergy between market integration conditions and technical potential in the case of Chile has a favourable basis due to progress in access to international trade made in the 1990s and early 2000s. This synergy is enhanced by an economic policy of greater competitiveness (non-distortion) in the markets of export industries, which allows for economic growth gains under certain conditions, as shown by (Edwards, 1993; Krueger, 1997; Rodrik, 1998; Rodríguez & Rodrik, 2000). Market access opportunities, with less distortions in domestic sectors, generate economic growth gains for countries with these exporting sectors.

Nevertheless, to develop Chile's technical potential for RE, it is important to consider the different market access and technical barriers that may hinder such development, as described in Sauma et al. (2011). These barriers are:

- Implementation of economic instruments enabled for technological competition: to promote optimal conditions for the production of renewable electric energy, production of green hydrogen and derivatives it is necessary to advance in allocative, productive and dynamic efficiency (see subsection 4.6).
- Installed capacity in transmission: For electricity generation, the integration of two markets such as the one observed between the Central Interconnected System (SIC) and the Northern Interconnected System (SING) to give way to the National Electric System (SEN) has revealed the relevance of investment in transmission, since it expanded both supply and demand in the market and provided greater flexibility in the supply of energy from different technologies with the reduction of bottlenecks in transmission. This example is illustrative when thinking about integration with international markets.
- Integration of industries and markets: For the creation of hydrogen hubs as technological development poles, sharing infrastructure costs and benefits, lowering transaction and operation costs, generating the market for supply and demand.

- Design of a joint regulation and market: To design the path to convergence in a common market in the long term, taking the first steps with bilateral agreements or contracts that adapt to the specific characteristics of each project and country. An important aspect for the export of electricity to neighbouring countries in Latin America.
- Certainty in interconnection agreements: The lack of stability of interconnections, through long-term contracts and other instruments that ensure stability and predictability of revenues and contractual commitments.
- Unequal distribution of benefits: Revenues related to congestion rents from interconnections should be shared equitably among countries (e.g., through a reduction in transmission system usage charges).
- Export regulatory framework: Lack of unconditional government backing from all countries involved in the operation of interconnections.

4.8. Policy alignment

RE projects, whether for exports or for local consumption, must be consistent with the principles set out in the different regulations and instruments that compose Chile's climate-change policy, namely, the NDC, the FLCC (to be approved), the Long-Term Climate Strategy, and the sectoral plans therein. In its NDC, Chile has stated its commitment "in advancing in a just transition and sustainable development," so that each of the commitments that the sectoral authorities have pledged therein must contribute to the fulfilment of the Sustainable Development Goals (SDGs). The projects included in the energy sector plans, such as the production and export of renewable energies, must comply with the principles of these general guidelines and their regulations. Therefore, they must abide by citizen participation standards and follow the territorial development vocations defined in the local governance bodies.

New infrastructure projects are carried out in a context that is a mixture of legislations expressly designed for them, and the current legislation that applies to those aspects that were not contemplated in such design. Since most of the social and environmental aspects that are present today in the national climate-change policy, were not considered in previous institutional frameworks, there are aspects of the current legislation that produce undesirable effects and are likely to contradict the guiding principles of the national climate change policy.

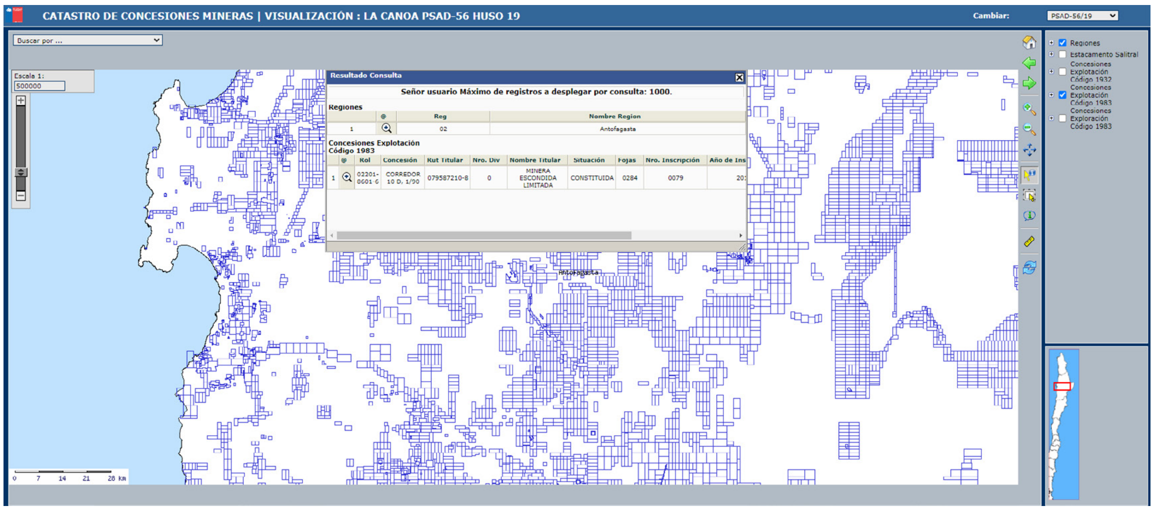
As an example, we describe the link between the current mining code and its importance for the development of new projects in some areas of northern Chile, which have high solar, wind and green hydrogen potential.

In the north zone of Chañaral, there is almost no land close to the coast due to the geomorphology of the area (coastal cliffs of more than 1,000 m adjacent to the coast, see Figure 13).Large industrial plants that require significant surface areas to host electrical substations, waste management, ponds, etc. are located in La Pampa, an area located in the plateau nearby, so most electricity transmission systems are installed in this area rather than on the coastline. Moreover, the solar radiation potential for photovoltaic generation is higher in La Pampa, so this area is very attractive for the development of RE energy projects.

Figure 13
Coastal cliffs in northern Chile
Source: Cristina Dorador, twitter, 3 Sep. 2021, https://twitter.com/criordor/status/1433877178576515072/photo/4

Due to environmental and landscape considerations, electrical infrastructure is buried underground, and is therefore governed by the mining code. Figure 14 shows the underground infrastructure that runs from the mountain range to the sea throughout long corridors protected by mining rights. It corresponds to Coloso port of Minera Escondida, largest copper mine, located in coastline and delimited for coastal cliffs of northern Chile with height greater than 900 m.

Figure 14
Area of Coloso port of Minera Escondida
Source: Catastro de Concesiones Mineras, Sernageomin, Gobierno de Chile.



The existing infrastructure belongs to private parties that control the access of new entrants. To prevent mining property speculation from interfering with new energy projects, it is necessary to modernise the mining code by moving to regulation models where mining property concessions are granted temporarily, ensuring that exploration and exploitation work is carried out within a certain period; if no work is carried out, the state can claim back the underground.

In addition, the basic geological information generated should be made public at the end of the project, and the state should be able to grant concessions to new actors, as is the case in Peru and Australia.

It could be a policy where critical energy infrastructure (aqueducts, mineral pipelines, among others) can be installed underground and parallel to existing public infrastructure (roads, highways and railways).

5. Synthesis and recommendations

This section provides a synthesis of the key aspects, which serve as a basis for recommendations.

In contrast to what is commonly thought, history shows us that Chile has sought to promote ambitious bets in the field of renewable energies at different moments. The current scenario offers an opportunity to realize the set of environmental, technical, political and economic elements to consolidate and project into the future the central role that renewable energy technologies can play for our sustainable development as a country.

As the first element of synthesis, we would like to emphasize that Chile's comparative advantage relies on its great renewable resources. The different energy export options identified are:

- Renewable electricity using electrical transmission grids.
- Hydrogen and by-products (synthetic fuels, fertilizers, other chemical products) through pipelines or maritime transport.
- Local production or manufacturing of products and services fed with RE.
- Knowledge and R&D capabilities.

These export options should be considered as possible means to take advantage of the large renewable energy potential and not necessarily as goals in themselves. This should not hinder the country from making ambitious bets. However, by seeing them as options leading to the same objective, it is feasible to develop a more robust strategy, taking into account the environmental and socio-cultural impacts of each one.

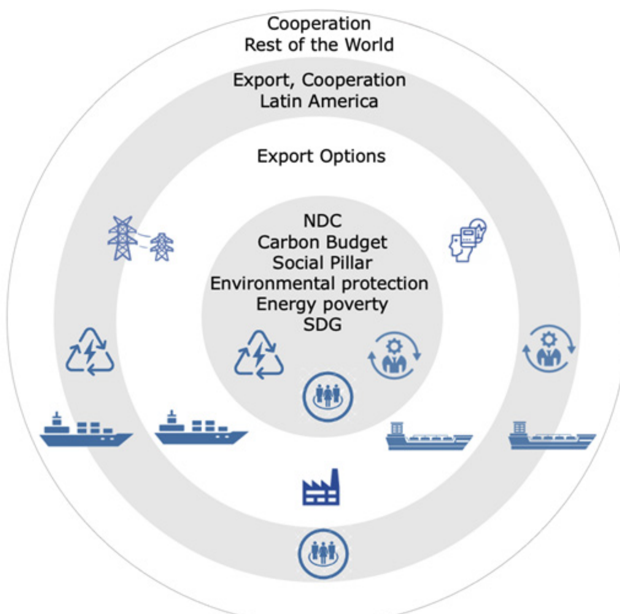
In that sense, the economic, legislative and regulatory measures to implement a strategy to export renewable energies will require a broad agreement. Such an agreement should be led by the national and regional authorities and would require the inclusion of diverse actors, namely, the public and productive private sector, academia and scientific community, as well as political and social organizations. This will ensure the sustainability and stability of the development policies finally implemented, avoiding socio-environmental risks..

5.1. General vision

Nowadays, the production and export of renewable energies have not been approached considering the solution of any relevant social problem for the country. Since it is not the objective of this report to provide a roadmap, it is proposed as a first recommendation that the production and export of renewable energies should respond to a mission that contributes to solving national socio-environmental challenges. An initial proposal to define this mission is "achieving energy sovereignty with renewables and in a just transition process" that can be a starting point for the participatory processes indispensable in determining social legitimacy. The current context of the constitutional discussion may provide a favourable space for defining a mission in this area.

The whole process of renewable energy exports should be framed as a part of the Chilean policy for climate change and the current local context presented in the previous sections, i.e., it must be consistent with the principles set out in Chile's NDCs, in the future FLCC, in its Long-Term Climate Strategy (ECLP acronym in Spanish), and in the mitigation and adaptation plans of the energy sector. Figure 15 shows a general overview of this vision.

Figure 15
General vision
Source: Developed by the authors.



The Chilean state, in the NDC, has stated its commitment "in advancing in a just transition and sustainable development," so each and every action related to climate change mitigation and adaptation should contribute to the fulfilment of the SDGs. The projects included in the energy sector plan, such as the production and export of renewable energies, must comply with the principles of these general guidelines and the regulations in force to comply with the NDCs. Therefore, they must abide by citizen participation standards and follow the territorial development vocations defined in the local governmental bodies. From this perspective, exports can also be articulated with cooperation in Latin America to project the region as an exporter of RE in some of its forms to the rest of the world. This would build a robust basis for international cooperation in the context of the Country Agreement.

Compliance with the NDC and export of RE from Chile can transcend the dilemma of conflicting objectives. The export potential could contribute to the achievement of national goals by providing scale and technological openness. The development of competitive, world-class capabilities to enable a just energy transition to carbon neutrality in Chile, as set out in the NDC, can be supported by the parallel development of an export sector. However, this virtuous relationship between sustainable local development and RE exports is not possible without public policies to guide it.

5.2. *Art.* 6 of the Paris Agreement and market integration

Although there is currently no regulatory or institutional framework that allows for an adequate articulation of Art. 6 of the Paris Agreement, in particular ITMOs, we have concluded that there is a possibility of synergy between the fulfilment of local targets (NDCs, etc.) and export options:

- ITMOs as enabling resources for compliance with national climate change and sustainability priorities.
- Need for a formal linkage between both processes (local targets and export options) to align them with climate change policies.
- Possibility of forming a cooperation platform at the Latin American level for the export of RE in different forms from Latin America to the world.

The current mechanisms, however, do not promote this synergy and are instead a source of conflict to meet both goals.

To develop Chile's technical potential for RE, it is important to address market access and technical barriers that may hinder such development with the following initiatives:

- Implementation of economic instruments for technological competition: to promote optimal conditions for the production of renewable electricity, production of green hydrogen and derivatives, it is necessary to incorporate the social cost of carbon and other externalities (taxes, norms or both).
- Transmission capacity: For electricity generation, the integration of local and regional markets through a timely development of new transmission capacity is critical.
- Certainty in interconnection agreements: The lack of sustainable interconnections schemes, through long-term contracts and other instruments that ensure stable and predictable revenues and contractual commitments.
- Integration of industries and markets: For the creation of hydrogen hubs as technological development poles, sharing infrastructure costs and benefits (RE generation, transmission lines, electrolysers, storage, harbours, among others), lowering transaction and operation costs, and generating the market for supply and demand.
- Design of a joint regulation and market: To design the path to convergence in a common market in the long term, taking the first steps with bilateral agreements or contracts that adapt to the specific characteristics of each project and country. An important aspect for the export of electricity to neighbouring countries in Latin America.
- Unequal distribution of benefits: Congestion revenues from interconnections should be shared equitably among countries (e.g., through a reduction in transmission system usage charges).
- Export regulatory framework: Lack of unconditional government backing from all countries involved in the operation of interconnections (state public policy).

5.3. *Renewable* energy potential and observatory

The main conclusions and suggestions in the field of renewable energy potential are:

- It is confirmed that Chile has a considerable renewable energy potential that can be the basis for various exports.
- However, assessments of potential do not yet fully incorporate:
- Environmental and biodiversity impacts (desalination plants, wind farms and migratory birds, among others),
- Socio-cultural impacts,
- Contribution of small-scale distributed generation (below 3 MW),
- Detailed projections of climate scenarios for the horizon 2050,
- Risk identification related to extreme weather events.
- Research and systematic observation will be a key concept for the continuous evaluation of the RE potential of Chile.

For example, due to the geographical characteristics of Magallanes, most of the bird migration routes pass through a very narrow stretch of land, and there is not a wide range of coastal areas to install windmills without affecting aerial biodiversity. A comprehensive study of bird migration patterns must be done before the installation of large wind farms in the Magallanes region. The urgency of these issues, which are already part of the decisions and commitments being made in Magallanes and northern Chile, is emphasised.

5.4. Legitimacy and social licence

The current decision-making context shows the relevance that the following elements and actions support the development of Chile's renewable energy exports to ensure its governance:

- RE export potential needs to be developed under a just climate action principle. This means that it must allow for an equitable allocation of costs and benefits, it should protect the most vulnerable communities, and at the same time it must reinforce environmental institutions, preserve biological diversity and ecosystems, and consider territorial priorities.
- Two regions in Chile have a clear RE export potential: Antofagasta and Magallanes. Any plan to develop this potential should be based on a territorial socio-ecological approach. This means, developed by the inhabitants of those regions, respecting their development vocations, socio-economic development needs and environmental limits, measured by their planetary boundary indicators.
- Applying an anticipatory principle, RE exports should allow the country to advance significantly in the capacity building of professionals for the sector.
- Overall positive impact on a small scale in the territories where they are developed.
- Community and citizen participation in the process.
- Contribute to the reduction of energy poverty at the national level.
- Adequate balance of policies and strategies at the national level with those developed and implemented at the regional and local level.
- The multidimensionality (technological, economic, socio-cultural, environmental) of the impacts of macro-projects and the inter-systemic connections of the transition processes towards renewable energy export should be considered.

Consequently, long-term renewable energy export policy should be inclusive and representative, incorporating all territories and localities, without exception, in the energy transition, whether they contribute directly to exports or not.

A policy of this nature, although ambitious, implies a greater involvement of the state and local governments in the transition efforts and allows several strategic objectives to be met simultaneously: increasing export capacity; complying with the NDCs and SDGs, and guaranteeing governance and social and political legitimacy to the export process.

5.5. *New* challenges for science and technology

As in other productive sectors, particularly the copper industry, the introduction of renewable energy sources represents a great challenge for Chilean science and technology. Indeed, beyond technical innovation applied to production processes, quantifying the impacts and benefits related to the generation, transport, storage and use of renewable energy will be necessary. This means efforts in different sciences, including economic, social and anthropological, computer, environmental and ecological sciences.

In this sense, a new industry could be generated, that invigorates the economy in a virtuous way, for the benefit of citizens and for Chile's position within the framework of international development. This will require a strong effort to build new scientific-technical capacities and competencies, with a strong impact on educational plans and programs at the technical and university level.

Specifically, the study has identified several research topics that would allow progress to be made in this field:

- Interdiscipline: Export development implications on sociotechnical systems. Energy transitions not only imply technological changes for energy infrastructure, but entail transformations in the social and cultural relations, enabling us to move towards new energy development. Interdisciplinary research frameworks are required to successfully address many of the challenges raised in this document.
- Circular Economy: To minimize further socio-environmental problems and conflicts, the transition should be carried out as part of a broader transition towards a circular, minimum-waste economy.
- Business Models: Integrated and collaborative research to propose innovative models of commercial and partnership agreements inspired by the sustainable development goals, in the context of international relations exchanges and market integration.
- Natural resources balance: Sustainability and environmental research to describe, measure and control the expected impacts of the emerging energy generation industry on climate change and natural resources systems (desalination, solar energy, wind energy, transmission lines, among others).
- Research and innovation for local requirements and conditions: Electrolysers, water treatment, storage, transportation, monitoring systems, advanced research on local RE sources (geothermal, solar, wind, hydro and biomass) enhancing their use and efficiency in the export options presented, end-use applications of hydrogen and derivatives (i.e. adoption of electrolysis-based hydrogen and other energy carriers, as biofuels), policy alignment, history of science, socio-cultural impacts, impacts on biodiversity, mitigation measures.

- Transportation systems: New transportation, logistic and storage systems, both on national and international exchanges (weight and volumes, energy efficiency, refuelling).
- Demonstration projects: Focus on demonstration projects with a science-based interdisciplinary validation and follow-up scheme.
- Technological transfer: Generation of new innovative models and strategies for the effective transfer from scientific research to the production sector.
- Objective evaluation of RE potential: Identification of favourable areas for installation of RE projects, based on geo-referenced factors that require restriction thresholds, according to technical, environmental, territorial, and socio-cultural factors.

5.6. The need for partnership

The following strategic partnership areas are highlighted:

- The need for research and commercial agreements with significant hydrogen purchasing centres or hydrogen-producing partners. For example, the collaboration between Japan and Australia should be an example to follow. It considers both countries' institutional arrangements and segregates the aspects that each party can bring to the table to achieve a common understanding of the entire green hydrogen maritime transport chain. In addition, the safeguards of green hydrogen production allow for its sustainability from the inside out at the time of export.
- Need to establish partnership agreements in education with Japan, Australia and Europe, for example, to integrate innovative technologies and complement it with the knowledge to achieve a just transition, greater acceptance and participation in the processes.
- Need to assess internal or Latin American demand for green hydrogen to become independent of "developed markets" that are limited to some countries that will look for the cheapest options. Also, explore the possibility of association with Latin American countries to build an associative model to boost hydrogen exports from Latin America to the rest of the world.
- Need to position itself as a real solution for decarbonisation compared to blue hydrogen initiatives.

5.7. The need to review and improve current legislation

A recently published report on Chilean climate governance (Billi et al, 2021) deems the current system insufficient to face the challenges of climate change. The report describes present governance as highly fragmented into different agencies and planning instruments that are highly disarticulated. Current governance also displays an excessive centralization of resources and a low consideration of territorial interdependencies, generating artificial separations among processes and components associated with the management of the different elements, and a lack of coordination in management.

In this contexts, today's legislation:

- Should be reviewed to identify aspects that can speed up and improve the development of new projects, as well as generate synergies with other sectoral authorities, for example:
- build geo-referenced cadastres for different components at national level based on information gathered by private parties for environmental impact assessments.
- build databases with the monitoring information that private parties must gather in the development and operation of their projects, and that are reported to different authorities. This information should be publicly available with a delay of no more than two years.

- build databases and baselines with information on detailed long-term mining plans for the entire life of the mine, even beyond the approved resolution of environmental qualification (i.e., Codelco's Ministro Hales Division, which has resolution until 2026, has been processing since 2019 the extension of the Continuity of Operations permit through).[53]
- Need to review existing national legislation to detect aspects that may hinder the aforementioned development (e.g., modernisation of the mining code that currently regulates underground infrastructure in areas with renewable energy generation potential in the north of the country).
- Need for the creation of a law that directly regulates the impacts of desalination plants. So far there are only initiatives and general guidelines to comply with the minimum requirements.

53 This information includes: movement of materials (waste and minerals); equipment requirements, number of extractions trucks, auxiliary equipment, future transport distances, among others; fuel consumption, diesel and gasoline; future electricity consumption, mainly for processes that depend on the hardness of future minerals to be processed. This information is currently not compiled by any state institution such as Sernagemin or Cochilco. With all this information, a much more robust, accurate and precise emissions baseline could be established.

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La UE es un socio estratégico clave en la acción climática y para conectar los puntos entre la Agenda 2030 y los Objetivos de Desarrollo Sostenible, en apoyo del logro de los objetivos del Acuerdo de París. En esa línea, Chile acordó trabajar conjuntamente con la UE en la preparación y organización de la COP 25.

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