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Perspective

Navigating the energy transition in South America: Regulatory challenges and trends in Chile's evolving energy legal landscape

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ABSTRACT

The Chilean electricity system is undergoing a profound transformation driven by climate goals and the imperative to reduce greenhouse gas emissions. This transition, characterized by significant state intervention and regulatory reforms, addresses the gaps left by market dynamics in achieving swift and comprehensive change. However, these changes bring challenges such as transitional risks and regulatory uncertainties that require the energy sector to integrate clean technologies while reshaping institutional frameworks. This article examines the regulatory challenges and trends in Chile's energy law, focusing on four pivotal areas: the just energy transition, the right to energy, market regulation for the transition, and frameworks for emerging technologies. Through a thorough review of these dimensions, the paper highlights recent legal advances, regulatory innovations, and critical areas for reform. By offering a comprehensive analysis, it aims to illuminate how legal and regulatory tools can support Chile's transition towards a sustainable and equitable energy system. This study contributes to the global discourse on the transition of energy by providing relevant insights for policymakers, researchers, and stakeholders.

1. Introduction

Sustainability transitions require state intervention, regulatory changes, and public investment to guide society towards ecological well-being, as markets alone cannot achieve these shifts within the necessary timeframe [1]. This is particularly true for Chile's energy transition, especially in the electricity sector, which demands new strategies and regulations to create a sustainable, efficient, safe, fair, and participatory system. Regulation plays a key role in this, as the energy transition represents a complete overhaul of industry regulation [2].

In its effort to meet climate commitments and reduce carbon emissions, Chile has made progress in adopting renewable technologies, and is seeking to also adopt important shares of green hydrogen and energy storage systems. However, the energy transition is not limited to technological transformation; it also requires addressing structural inequalities in energy access and ensuring an equitable distribution of benefits [3], as well as changes to institutional structures, regulation, and public policies [4].

Adapting the regulatory framework is a crucial challenge in the Chilean energy transition. [5] argue that regulatory flexibility is essential to respond to technological changes. At the same time, [4] warns that this flexibility should be accompanied by measures that ensure equitable access to the benefits of the transition. Inadequate regulation could exacerbate inequalities, creating barriers that hinder access to clean technologies for vulnerable communities and limiting the participation of local actors in the energy market [3].

This paper reviews new trends and challenges in Chilean energy law within this transformative context, analyzing how current and proposed regulatory frameworks are adapting to support the energy transition. We assess key legal and policy developments, evaluate recent regulatory innovations, and identify areas for further reform.

First, the conception of a just energy transition will be addressed, with special attention to the needs of participation of people and communities. Next, the recognition of the right to energy, its sources and content will be discussed, and then its development and debate in Chile will be analyzed. Subsequently, a review of the economic regulation of the electricity market with potential to achieve the objectives of the

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energy transition in Chile will be made and, finally, an analysis of the necessary regulatory framework that allows the development of new energies and technologies necessary for the transition, such as green hydrogen and energy storage.

Through this analysis, we aim to provide insights into the evolving landscape of Chilean energy law, shedding light on the regulatory adjustments essential for a sustainable and inclusive energy transition.

2. Methodology

This paper employs a documentary review to analyze key legal and regulatory shifts in Chile's electricity sector related to the energy transition. The review draws on primary legal texts, policy documents, academic literature, international frameworks, and expert reports to understand how regulatory adjustments contribute to new technologies, public participation, and the socio-environmental priorities of a just energy transition.

Through thematic analysis, the review examines emerging regulatory issues, with a focus on justice dimensions like the just energy transition and the right to energy. It also explores legislative changes in the electricity sector driven by decarbonization goals and new regulatory areas that require further development.

The review follows a structured sequence, beginning with foundational principles and moving towards specific regulatory issues, focusing on post-pandemic developments. This approach captures the contemporary dynamics of Chile's energy transition, offering insights into both its achievements and regulatory gaps, and critically assessing the effectiveness and future needs of Chilean energy regulation.

3. Just energy transition

Zero carbon emissions from the energy systems must be ensured to meet targets established in the Paris Agreement, which requires systemic challenges and vast investment ahead [6]. As part of this transition, the energy systems of different countries are facing increasing requests to address economic, social and environmental issues related to the energy sector [3,7]. This means supplying affordable and reliable energy, but also reducing inequalities and environmental impact [8].

The International Labor Organization has indicated that the term "just transition" means making the economy as fair and inclusive as possible for all individuals or groups involved, creating proper work opportunities and leaving no one behind. This entails both maximizing the social and economic opportunities arising from climate action and minimizing and carefully managing the challenges. Effective social dialogue between all affected groups and respect for the fundamental principles and rights of working people are tools for this [9]. In Latin America, where structural changes in energy pose particular challenges such as informal labor and poverty, a just transition is both an urgent and complex goal [10].

A just transition involves addressing three fundamental dimensions of justice: distributive, procedural, and recognition. Distributive justice focuses on redistributing benefits and costs, ensuring that vulnerable communities are not marginalized in the process. Procedural justice requires transparency and inclusiveness in decision-making so that all affected groups have a voice in the transition process. Lastly, recognition justice requires highlighting and respecting the specific experiences and needs of historically excluded communities, such as women in renewable energy projects, who often face barriers in decision-making and receive unequal benefits [7,11].

The concept of a just transition involves maximizing the social and economic opportunities of climate action while minimizing its adverse effects on the most vulnerable communities. Policy design should focus on distributive justice and climate justice, considering equity in the distribution of costs and benefits [5]. From a broader vision, [1,11] consider procedural justice and recognition justice, essential factors for an equitable and legitimate transition. In the Chilean context, where territorial and socioeconomic inequalities are profound, the approach from [5] may benefit from integrating procedural justice and recognizing the experiences and needs of local communities, thereby ensuring an inclusive and legitimate process.

The risk of reproducing inequalities is a significant challenge in the energy transition. In this sense, the regulatory framework and public policies play an essential role in preventing the shift towards a sustainable energy matrix from exacerbating existing inequities. Chile, for example, faces the challenge of implementing a socially and ecologically just transition, which not only considers decarbonization but also promotes social and environmental resilience at all levels. In 2022, Chile incorporated this concept into its Nationally Determined Contribution (NDC), emphasizing the need for a participatory approach that empowers communities and addresses justice from multiple scales and dimensions [7].

The role of companies and regulators in a just transition is also crucial. Companies must ethically manage the social impact of their projects, including renewable energy projects that, while aimed at reducing emissions, can negatively impact local communities if not properly managed. This is particularly relevant for projects that affect women and other vulnerable groups, who require greater inclusion in planning and decision-making processes [12] . For their part, regulators must assess whether changes associated with the energy transition lead to the creation of fairer systems or, conversely, perpetuate structural inequalities. A truly just transition must ensure that energy policies, such as carbon taxes, do not have regressive effects and that compensation mechanisms are implemented to benefit low-income communities [10,13].

So far, public policies on just energy transition have focused on accompanying the closure of coal-fired power plants, as indicated in the "Strategy for Just Transition" launched by the Ministry of Energy [14]. The recent creation of an Office of Socio-Ecological Just Transition under the Ministry of Environment and an Interministerial Committee on the subject, of which the Ministry of Energy is a member, seeks to provide a governance framework for a just energy transition. Additionally, the recent Just Socio-Ecological Transition Plan of Tocopilla was developed with the goal to effectively and appropriately address the problems, needs, and projections of the local community during the closure of thermoelectric plants [15].

Critical minerals, such as lithium, risk reproducing injustices [16]. In Chile, debates center on balancing large-scale exports with value-added production [17]. Recognized as strategic for energy storage and the transition, lithium is subject to state control aimed at leveraging Chile's geopolitical position [18]. However, the energy transition may exacerbate socio-environmental conflicts tied to extractivism and resource exploitation [19].

Chile's energy transition demands a multidimensional approach that integrates decarbonization with distributive, procedural, recognition, and socio-ecological justice. Achieving a just transition requires both theoretical alignment and practical steps towards inclusivity and fairness. Chile's commitment to a socially and ecologically just transition makes it a key case study in balancing decarbonization with structural inequality and equitable development.

4. Right to energy

Although the origin of the discussion on an eventual right to energy is not entirely clear, in practical terms, this debate has been carried forward even though it has not been explicitly enshrined in the different legislations [20]. So much so that, this issue attracted the attention of agencies such as the United Nations (UN) -which in 2012 proclaimed the "International Year of Sustainable Energy for All" and the European Union (EU) [21]; it has also nurtured the debate in the political–legal currents around the "new constitutionalism" or "critical constitutionalisms" [22], and motivated profound and relevant discussions in Chile since 2016.

In the eyes of the legal dogma derived from International Human Rights Law and the international courts of justice, this issue is framed within the conflicts arising from the discussion on the justiciability of third-generation human rights [21,23–25]. In this regard, and without express legal recognition, there are important advances within the European Union that give indications about the possibility of configuring a framework of rights for energy based on jurisprudence. Thus, Directive 2019/944 [21] recognized that the affordability and necessity of energy services are relevant elements within the fundamental guarantees of the citizens of the Union (recital 59). Nevertheless, based on [26], these debates still fail to achieve concrete legal impacts as there would still be conceptual divergences in answering questions such as: what is the right to energy?

The right to energy is central to contemporary energy justice debates, encompassing diverse approaches. [27–29] argue it is a human right essential for dignity and overcoming energy poverty, initially focusing on rural areas and later on clean energy transitions. [30] emphasizes access and use, advocating for universal policies beyond market frameworks to ensure equity and well-being. [31] highlight the adoption of rights-based language to protect vulnerable populations, while [32] classify the right to energy into fundamental, incremental, and complementary dimensions, linking it to justice and sustainability. Finally, [33,34] stress the need for redistributive strategies and state commitment to prioritize equitable energy access for a just transition.

4.1. Chile and the road to the right to energy

As we have already mentioned, the discussion on the right to energy in Chile has undergone a significant evolution in recent years, marked by the development of public policies and the implementation of strategies aimed at guaranteeing access to energy, promoting renewable energies and ensuring sustainable energy development. In Table 1 a brief review is detailed of the public policies adopted by the State of Chile in recent years that are related to the debate on the right to energy.

The debate on the right to energy in Chile has advanced through policies promoting access, renewables, and sustainable development. This paper analyzes public policy instruments (Table 1) that address practical challenges, showing how incremental changes advance the right to energy despite the lack of an explicit legal framework. This focus connects the right to energy with social and economic realities.

This sequence of public policies and national strategies shows how issues such as equity, sustainability and gender perspective in the energy sector have been gradually positioning themselves in the political discourse, outlining the main elements of the discussion on the right to energy in the country. These policies not only fostered the discussion on the need for cleaner and more sustainable energy sources, but also began to establish the debate on the right to energy as a crucial element for social and economic development.

Thus, with the issuance of the ‘‘Chile Energy Policy 2050’’ in 2016, Chile marked an important milestone by establishing a long-term vision focused on non-conventional renewable energies and sustainability. In doing so, it not only addressed the need for a reliable and environmentally sustainable energy supply but also, laid the groundwork for discussing access to energy as a fundamental right that must be guaranteed for all citizens. Another impulse in the same line meant the ‘‘Energy Route 2018–2022’’, deepening the need to modernize the sector’s regulations and policies, promoting energy efficiency and access to clean energy.

An interesting development is the document on equitable access to sustainable energy in 2021, which not only refers to the urgent need to improve access to energy but also enshrines for the first time the phenomenon of energy poverty as a task of the State of Chile, highlighting the direct link between the right to energy and social justice as a basic element.

A turning point is the Energy 2050 update in 2022, together with the Gender and Human Rights Yearbook, which ratifies the State’s commitment to the inclusion of broader social dimensions in energy policy such as gender equality and human rights.

Finally, one of the last relevant efforts was the creation of an Interministerial Committee for a Just Socioecological Transition, which, although it does not explicitly mention the right to energy, is implicitly related to this notion by considering on the one hand the Ministry of Energy as a member of this committee and, on the other hand, sustaining that energy policies are a key component in the socioecological transition.

In summary, the development of these public policies in Chile reflects a paradigm shift towards a conception of the right to energy that is comprehensive, inclusive and sustainable. This approach not only seeks to solve environmental and economic challenges but also installs the issue of the right to energy as an essential component of the debate on human rights and social justice in the country. This process of change shows how energy policies can and should play a crucial role in promoting human, economic and social development.

4.2. The right to energy in the constitutional debate in Chile: the Constitutional Convention (2021–2022)

The Constitutional Convention (2021–2022) was a democratically elected constituent body tasked with drafting a new proposed Constitution for the country. This instance was established as a result of a process of social protests that began in October 2019, known as the ‘‘Estallido Social’’, and which demanded, among other things, profound changes that were incompatible.

The Constituent Convention (2021–2022), formed after the 2019 "Estallido Social" protests, was tasked with drafting a new Constitution to address demands for profound changes incompatible with the political-economic model of the 1980 Constitution and its post-1989 reforms [35,36].

This Convention addressed the issue of energy from a perspective oriented towards sustainability, environmental protection and recognition of the rights of communities and indigenous peoples regarding natural resources. The proposed Constitution reflected these approaches in several of its articles, seeking to establish a framework that would promote an energy transition to cleaner and renewable sources, as well as ensure a vital minimum of energy, and promote socially and environmentally responsible management and exploitation of energy resources. This perspective was enshrined in Article 59 of the proposal, which stipulated the following principles detailed in Table 2.

In broad terms, the Convention enshrined an ‘‘Energy Charter’’ that not only focused on basic access but also contemplated aspects such as social justice, environmental sustainability, citizen participation and energy security as essential components for its full realization. Another highly relevant aspect of this initiative was that the notion of energy was never subordinated or limited to any particular energy (e.g. electric, fossil, solar, wind, nuclear, etc.) and the reference was always understood universally, generating a great innovation if we compare it with the rest of the legislations of the countries that served as the basis for this initiative.

Some proposals to continue the debate already started could be along the following lines:

1. Specific legislation: laws that explicitly articulate the right to energy.
2. Citizen participation in energy management: promote mechanisms for citizen and community participation in planning, decision-making and management of energy resources, strengthening the role of cooperatives and local organizations.
3. Improve equitable access to energy: implement programs that ensure access to basic energy services to vulnerable and isolated communities, prioritizing small-scale renewable energy projects and self-consumption.

Table 1
Public Policies and Right to Energy 2016–2023.

Year	Public policies and/or national strategies	Content related to the right to energy
2016	Energy 2050. Energy Policy Chile 2050.	The "Chile Energy Policy 2050", published by the Ministry of Energy, establishes a long-term vision for the country's energy sector. This policy focuses on the growth of non-conventional renewable energies (NCRE) and the transition to a more sustainable and low-carbon energy system.
2018	Energy Route 2018–2022.	The "Energy Route 2018–2022" is another key initiative that seeks to modernize energy sector regulations and policy, promoting clean energy-based technologies, efficient transportation, and improved quality of life for citizens. This strategy has led to a significant increase in installed solar and wind power capacity, as well as in total renewable energy generation is a key initiative aimed at modernizing energy regulations and policies, promoting clean energy technologies, efficient transportation, and enhancing citizens' quality of life.
2021	Equitable Access to Sustainable Energy: Public policies to combat energy poverty in Chile.	This document emphasizes the importance of ensuring universal and equitable access to quality energy services, which is essential for the reduction of energy poverty and social development. .
2022	Energy transition in Chile. National Energy Policy 2050. Update.	The update of this policy in 2022, under the title "Chile's Energy Transition", reinforces the country's commitment to climate action, the improvement of quality of life through equitable access to energy and the development of a new productive identity that includes social and environmental sustainability.
2022	Gender and Human Rights Yearbook Advances 2022 and Challenges 2023.	This document from the Ministry of Energy highlights advances in gender and human rights in the energy sector, suggesting a consideration of energy as a human right.
2023	Decree 57 of 2022 of the Ministry of Energy	Established the creation of the "Interministerial Committee for Socioecological Just Transition". The purpose of this committee is to advise the President of the Republic on issues related to the policy and institutional transformations necessary to advance in a process of Socioecological Just Transition.

Table 2
Principles of Article 59 and Right to Energy.

Principle	Relationship with the right to energy
Accessibility and Affordability: Ensuring that all people have access to a vital minimum of energy that is safe and affordable, emphasizing the importance of energy being accessible to all, without discrimination.	This principle is fundamental to the recognition of the right to energy, ensuring that all people can access the basic energy services necessary for a dignified life at a cost they can afford. Affordability and accessibility are essential to ensure that no one is excluded from access to energy for economic reasons.
Equity: Ensure equitable access to energy, emphasizing that access to energy should be fair and should not discriminate between different groups or regions.	Equity in energy access implies that the right to energy is guaranteed equally for all people, without discrimination based on geographic location, socioeconomic status, or any other factor. It promotes social justice by ensuring that vulnerable groups and less developed regions have adequate access to energy services.
Environmental Sustainability: Promote an energy matrix based on renewable energy sources with low environmental impact, reflecting a commitment to environmental sustainability and the fight against climate change.	By linking environmental sustainability with the right to energy, it is recognized that access to energy must not compromise the health of the planet and future generations. This principle reflects the need to move towards renewable energy sources and low environmental impact energy systems to ensure a long-term sustainable right to energy.
Decentralization and Diversification:Promote an energy infrastructure that is distributed, decentralized and diversified, which can contribute to energy security and resilience in the face of energy crises or social and natural disasters.	Decentralization and energy diversification are directly related to energy resilience and security, key aspects of the right to energy. By promoting more distributed and diverse energy systems, dependence on single sources is reduced and the capacity to respond to crises or supply disruptions is increased.
Public Interest of Energy Infrastructure: Consider energy infrastructure as being in the public interest, stressing the importance of this infrastructure serving the common good and oriented towards the benefit of society as a whole.	Considering energy infrastructure as a public good reinforces the notion that access to energy is a basic right and a priority for social and economic development. This principle underscores the State's responsibility to guarantee and protect access to energy for all.
Promotion of Cooperation and Self-consumption: Encourage cooperative energy companies and self-consumption, promoting forms of energy organization that promote citizen participation and self-management of energy resources.	This principle promotes the active participation of citizens and communities in energy management, recognizing the right to energy as an aspect that can be managed collectively. Encouraging self-consumption and energy cooperatives democratizes energy production and management, empowering people and communities in their relationship with energy.

4. Education and awareness-raising on energy sustainability: include in educational curricula content on energy, sustainability, and climate change, promoting a culture of responsible consumption and knowledge of renewable energy sources and their benefits. The continuation of the debate should focus not only on consolidating the progress already achieved but also on addressing the gaps and challenges that remain to be addressed to ensure a just, sustainable and participatory energy future.

Unfortunately, the 2023 constitutional process, with its more conservative orientation, sidelined energy and environmental issues, leaving discussions from the 2022 process unaddressed.

5. Regulation of electricity markets for the energy transition

To achieve the objectives of a just energy transition, the State, companies and the community must carry out actions aimed at meeting these objectives. Thus, the most important role of the State is to create the most favorable legal and regulatory conditions for the development of a sustainable, safe, efficient and participatory energy sector.

In the Chilean case, particularly in the electricity sector, the energy transition has been successful in one of its most recognizable objectives, which is to achieve system sustainability [37]. However, this policy must also meet objectives aimed at decentralizing generation and encouraging demand-side participation, all of which are essential for economic development, security of supply and, of course, sustainability [38].

Chile has all the conditions to successfully face these threats, since it has already overcome the dilemma of underdeveloped countries and has opted for sustainable development, materialized in a comprehensive energy policy and the subscription of international commitments aimed at this objective [39].

Active civil society participation is crucial for a just energy transition, as it fosters greater acceptance and understanding of energy policies [40]. Since social groups are diverse, effective participation requires tailored knowledge to ensure positive outcomes [41].

In the case of distributed generation as a participation mechanism, it has been shown that participation will be conditioned by factors such as infrastructure, the technology used, geography and the communities themselves, so that regulation must be adjusted to these different contexts [42].

In the Chilean case, the participation of individuals and communities in the electricity markets is extremely limited, since only through Law No. 20571 on distributed generation, the participation of users in the market is allowed, but it only reaches a limited spectrum of users, due to the high investments required and the few benefits obtained in the medium and short term [37].

In this regard, a pending challenge for the Chilean electricity sector is to establish a regulation to allow and encourage the participation of renewable energy communities, in which an organization constituted and controlled by partners located close to the project can generate or store renewable energies to generate social, economic, energy and environmental benefits for its members [43,44].

Community participation in energy projects is currently limited to environmental regulations, involving only directly affected communities and some NGOs in later stages. Regulations should include citizen participation from the early stages, with information sharing, consultation, and co-participation, as recommended by the Organisation for Economic Co-operation and Development (OECD) [45].

This lack of participation has serious consequences as it generates a high level of conflict, especially environmental, that confronts communities with investors, delaying projects that are essential for the energy transition. This situation, in Chile, has significantly delayed and increased the cost of transmission projects, which are essential to adequately incorporate renewable energies into the electricity system, making them less competitive for other more polluting energy sources [46].

Concerning the efficiency objective in the energy transition, the aim is for the electricity system to generate sufficient energy at the lowest possible cost, and for people to make intelligent and reasonable use of the resource. This objective is particularly considered in the United Nations Agenda 21, as central to reducing greenhouse gas emissions [47].

One point where it is essential to improve efficiency levels is in household energy consumption, bearing in mind that around one-fifth of CO2 emissions come from this source and that it has increased by 1% per year since 2000. In this regard, a study on household consumption in different countries has shown that in most countries there is a lack of information, which hinders the development of effective public policies; that the greatest growth in consumption is due to heating, ventilation and air conditioning (HVAC) systems; and that emerging countries are increasing their residential consumption with greater intensity. To address the problem, it is proposed to motivate families to move to more efficient housing, to promote energy efficiency in products and thermal characteristics of buildings, and to stimulate behavioral changes towards conservation habits [48].

The regulation of the Chilean energy sector has taken care of this problem, highlighting the recent Energy Efficiency Law No. 21.305. It creates the obligation to periodically issue a National Energy Efficiency Plan, which must address various aspects of energy consumption, within which contemplates a series of requirements for companies to achieve higher levels of efficiency, applying penalties in case of non-compliance. In this sense, Decree 163 of 2021 of the Ministry of Energy is relevant, which establishes criteria to determine which companies are subject to the obligations described above, limiting it only to large companies.

Another important regulation in terms of efficiency is given by the atmospheric prevention and decontamination plans established in Law 19.300. Although the main objective of these plans is to contain and reduce pollution, they have important effects in terms of efficiency, such as establishing minimum efficiency levels for thermal systems, the obligation to improve the thermal efficiency of homes, and granting subsidies for this purpose. An example of the above is found in the Metropolitan Region Atmospheric Prevention and Decontamination Plan, established by Supreme Decree No. 31, of 2017, of the Ministry of the Environment, which establishes measures such as those described above in Articles 37 and 88.

Although it is difficult to quantify the results of these measures, the energy intensity index, which is the ratio of energy consumption to Gross Domestic Product (GDP), is illustrative. In Chile, although there is still no decoupling between economic growth and energy consumption, energy consumption has managed to grow at a slower rate than GDP [49].

Closely linked to efficiency are smart grids and smart metering systems, consisting of constantly evolving hardware and software based on information technologies and digitization. These systems have been empirically proven to reduce energy consumption and moderate energy inequality [50].

On this point, Chilean electricity regulation has shown little progress, mainly due to the almost null penetration of smart metering in end consumers, which despite its incorporation as part of the mandatory Technical Standard of the sector, for mainly political reasons it has not been implemented [51]. Specifically, the population is distrustful of these instruments, in addition to not wanting to assume the costs of changing the meter, which, by application of articles 120, 184 and 190 of the General Law of Electric Services, must be considered when determining tariffs.

Another key factor for the energy transition is the existence of an efficient electricity market, which requires regulation that corrects the sector's market failures so that, whenever possible, companies can make profits and recover their investments. In this sense, the prices paid for the services of the different segments of the electricity system

must correspond to their real costs.

However, a market that reflects real costs may generate negative effects for the energy transition, so it is recommended to adopt measures, highlighting carbon pricing, to reduce emissions and encourage technological innovation. Some research concludes that these measures encourage investment in more efficient technologies, but raise the cost of living, which can be offset by supporting poorer households through the additional income produced by the measure [52].

This is corroborated by a recent modeling study of coal pricing in Israel, which concludes that modest pricing could reduce greenhouse gas emissions by 67 % by 2050, but recognizes market effects that require active policies by the state, supporting the most disadvantaged sectors with the measure [53].

The risks of price distortions in the Chilean electricity market are latent, mainly due to the incorporation of the price stabilization mechanism established by Law No. 21,185 and 21,472, which implies that, to a large extent, it is the electricity generators that assume the cost increases momentarily, to the detriment of the smaller generators.

Currently, significant increases in electricity prices are projected due to the debt that the system has with these companies, which is why a bill has been approved to mitigate this increase and pay the debt, which would only be achieved in 2035.

Finally, an important challenge for the Chilean electricity sector is to consider regulations that impact the sustainability of medium-sized electricity systems (capacity greater than 1.5 MW and less than 200 MW) and isolated systems for small consumers (less than 1.5 MW), which operate separately from the National Electricity System. It is necessary to allow and promote the sustainability of these systems, with measures tending to incorporate sustainability as a planning and operation principle, guaranteeing open access to these systems for generators that operate with renewable energies.

6. Regulatory framework for new energies and technologies

6.1. Green hydrogen

Hydrogen is currently in a state of regulatory transition, from a historical consideration as a mere chemical to characterization as a crucial energy vector in the decarbonization of sectors difficult to electrify and in the energy transition. The regulatory framework for hydrogen as an energy carrier is still poor worldwide and some barriers to its long-scale deployment yet persist, also in Chile [54–57].

Chile has adopted a national green hydrogen strategy to guide the promotion of this industry as one with a key role in the country's energy transition [58]. A participatory process led to the publication of an action plan for 2023–2030, containing 30 measures to foster the hydrogen sector and overcome current barriers [59]. A Green Hydrogen Strategic Committee was also involved in the development of the plan, tasked with providing a broad consensus on strategic and policy guidance [60].

The government has also created a governance structure for the sustainable development of green hydrogen in Chile. In 2022 it created a Green Hydrogen Industry Development Committee, led by an Interministerial Council chaired by the Ministry of Energy and whose Vice-Presidency oversees the Production Development Corporation (CORFO). The Committee's mandate is to influence all decisions of public institutions associated with the allocation of resources, procedures, and commitments to implement the Green Hydrogen Action Plan [61].

Hydrogen was legally defined as an energy vector in 2021, paving the way for regulation. However, comprehensive regulation for the entire hydrogen value chain is still lacking, as is a clear legal definition of "green" hydrogen [62].

Some infra-legal instruments, such as safety regulations for hydrogen projects and environmental impact assessments, have been adopted [63–65]. Moreover, fiscal and financial measures have been introduced to promote the industry [66,67], as well as an interpretation on territorial planning to ensure that hydrogen facilities receive the same treatment as any other energy facility [68].

Moreover, budget laws since 2022 have earmarked specific resources, administered by the CORFO, to promote green hydrogen research and innovation. As [69] states, this is essential for the creation of a green hydrogen ecosystem.

However, hydrogen-derived fuels like methanol and ammonia lack specific regulatory frameworks, despite existing export markets for Chilean ammonia [70]. Also, some concerns about threats to biodiversity [71] and hydrogen safety hazards [72] have been voiced by civil society. This, alongside the lack of territorial planning in some of the areas identified as potential hydrogen hubs [73], may translate in backlash against this new industry if not addressed properly, jeopardizing the feasibility of projects.

Finally, given that the cost of green hydrogen is still higher than required for its large-scale deployment [74], it has recently been possible to evidence a decrease in the expectation around this technology. This opens the question about the usefulness of modifying the strategy by opening up to other definitions of hydrogen (such as low-carbon hydrogen, as it has been pointed out in the EU) [75], or with the aim of redirecting public policy efforts on renewable electrification rather than on boosting this new technology (see Table 3).

6.2. Energy storage

Storage systems are a crucial technology for the energy transition [76,77]. This is also the case in Chile, where there is an important transmission congestion that is causing huge curtailment of RES [78].

The Flexibility Strategy, formulated by an expert advisory committee emphasized the need for a regulatory framework for flexible storage systems and new flexible technologies [79]. Storage facilities are legally allowed to be remunerated in the ancillary services market [80], and recent laws allow storage technologies, including electric vehicles, to engage in the electricity market.

Additionally, legal recognition of generation–consumption systems ensures that charges apply only for energy withdrawn from the grid, not for self-generated energy [81]. Recently, the Ministry of Energy announced a regulation of this norm to provide greater interpretative clarity regarding its application.

Further initiatives for storage promotion include updates to the National Electric System regulations [82], land allocation for storage in strategic substations [83], and the adoption of a technical guide for environmental assessments [84].

All these measures allow to continue advancing the energy transition process and to foster the required investments to achieve the decarbonization of the Chilean economy. However, challenges remain in integrating storage into the electricity system due to outdated legal frameworks, such as the 1982 General Law of Electrical Services, which does not accommodate modern storage technologies within any of the three categories defined by the law.

7. Conclusion and policy implications

The energy transition tackles economic, social, and environmental challenges, with a focus on fairness and inclusivity. In Chile, this involves social dialogue, workers' rights, and community engagement for equitable benefits. Despite governance frameworks, opportunities remain for stronger regulatory approaches to achieve a just transition.

The Chilean constitutional process (2021–2022) recognized energy as a fundamental human right linked to sustainability, equity, and development. The proposed "Energy Statute" emphasized renewables and community participation, but implementing these principles in legislation remains a challenge.

Debates continue on the scope of the right to energy in Chile. While access has improved, significant gaps persist, particularly in

Table 3
Regulatory environment of green hydrogen in Chile.

Enablers	Opportunities for improvement
Ambitious goals in national strategy and action plan for strategy implementation.	Deadlines for the implementation of the action plan.
Definition of hydrogen and its derivative fuels as energy carriers.	Safety regulations for specific hazards of hydrogen as an energy vector.
Treatment of hydrogen in territorial planning as energy infrastructure.	Regulatory treatment of hydrogen-derived fuels.
Specific guidelines for the development of hydrogen projects.	General legal framework for the hydrogen industry.
Public initiatives for hydrogen project financing.	Permanent incentives for hydrogen R+D+i.
Definition of strategic hubs for the hydrogen industry.	Significant areas in the hubs without territorial planning aligned with the strategy.
Increasing energy costs.	Plentiful renewable resources.

establishing a robust legal foundation. Enshrining this right in law could advance policies addressing energy poverty and international commitments like SDG 7.

Chile has progressed in economic regulation, promoting sustainability and efficiency while supporting policy goals. However, greater attention is needed for the social aspects of the transition and community participation. Strengthening the legal framework for the right to energy could enhance public policies and reduce energy poverty.

Emerging technologies, such as green hydrogen, require new regulatory adaptations. A comprehensive framework for hydrogen and further development in energy storage regulations are critical to unlocking their potential.

Key policy implications for Chile's energy transition include:

1. A strong regulatory framework promoting social, economic, and environmental justice while advancing critical technologies.
2. Recognizing energy as a human right, focusing on accessibility, affordability, and sustainability.
3. Advancing regulations beyond technological neutrality to further the energy transition.

CRediT authorship contribution statement

Fernanda Skewes: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Óscar Guzmán:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julián Cortés:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Rivera:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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