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From Global to Local: Learning from Worldwide CSP Successes to Drive Chile's Solar Power Industry Forward

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Abstract. Concentrated Solar Power (CSP) technology offers a promising solution for enhancing the stability and reliability of renewable energy systems, particularly in regions with high solar resource availability like Chile. However, CSP deployment faces significant challenges, including technological mistrust, high costs, and regulatory barriers that hinder its growth. This study provides an in-depth analysis of global CSP successes and identifies key strategies and challenges relevant to Chile's context through a mixed-methods approach, including a comprehensive literature review and stakeholder interviews with key players in the Chilean CSP industry. The results reveal significant technological, regulatory, and financial barriers to CSP deployment, including issues with thermal energy storage (TES) systems, specifically the failures of molten salt tanks. Despite recent declines in CSP capital expenditures and the potential for further cost reductions, the study highlights the critical need for regulatory reforms and tailored policy support to address current market and technological limitations. Key recommendations include enhancing R&D investments to improve TES reliability, streamlining permitting processes, and fostering public-private partnerships to unlock CSP's full potential. The findings underscore the necessity of strategic incentives and business model innovations to enable the commercial-scale deployment of CSP in Chile, ultimately supporting the country's decarbonization goals and strengthening energy security.

Keywords: CSP, Energy Policy, Public-Private Partnerships, Regulatory Reforms

1. Introduction

CSP has emerged as a significant player in the realm of sustainable energy solutions, demonstrating notable success in several installations around the globe, as shown in Figure 1. These successes hinge on a complex interplay of factors including solar resource potential, electrical market dynamics, and policy frameworks, such as economic incentives like subsidies. In exploring these dimensions, the unique situation in Chile, a country with the world's greatest potential for direct normal irradiation (DNI) [1] but home to only one CSP project, the Cerro Dominador plant, presents a striking contrast. Despite its exceptional solar resource, Chile shows a conspicuous gap in CSP development, lacking immediate plans for new projects.

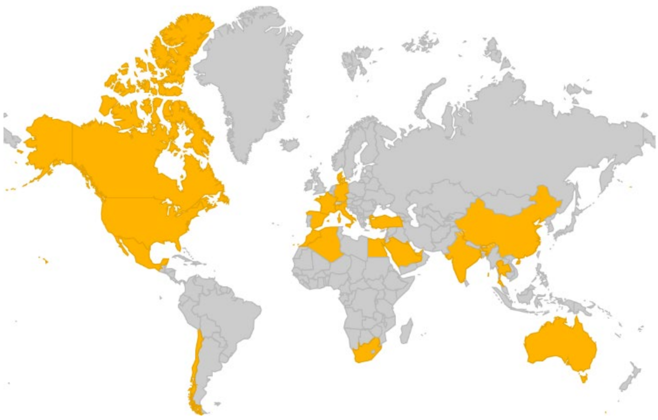

Figure 1. *Countries with CSP technologies worldwide [2].*

This study conducts an analytical review of successful CSP plants worldwide to identify the conditions and strategies that have facilitated their commercial deployment. The primary objective is to uncover key factors driving CSP development and assess how these strategies can be adapted to Chile's context. Given Chile's exceptional solar potential, this research is critical for enhancing the country's renewable energy mix and addressing grid stability challenges posed by the high penetration of variable renewable sources. CSP's inherent thermal energy storage capabilities provide a strategic advantage, enabling continuous power supply during periods of low solar availability and strengthening the resilience and reliability of Chile's national grid.

2. Methodology

This study employs a mixed-methods approach, combining an exhaustive literature review with primary data gathered from in-depth interviews with key stakeholders in the Chilean CSP industry, collected from the study developed by the Energy Partnership Chile-Alemania program [3]. These interviews aimed to identify perceived risks, expectations on technological costs and evolution, dominant future technologies, and necessary business and regulatory changes to enhance CSP development. Insights from literature, such as the effectiveness of national incentive programs for CSP as discussed by Perez et al. [4] and the impact of international finance institutions on CSP deployment in emerging markets by Frisari and Stadelmann [5], provided a comparative backdrop for our stakeholder analysis. This qualitative data complements the comparative analysis of global CSP policies, providing a grounded perspective on local industry challenges and expectations.

3. Literature review

The Paris Agreement, established in 2015, set ambitious global targets for decarbonization, aiming to limit the global temperature increase to well below 2°C above pre-industrial levels, with a more stringent goal of 1.5°C [6], [7]. Achieving these targets requires substantial reductions in greenhouse gas (GHG) emissions across all sectors, particularly in energy, which remains a significant contributor to global emissions [8]. In this context, Chile has committed to achieving carbon neutrality by 2050 as part of its decarbonization strategy, outlined in the long-term energy planning for 2023-2027 period (PELP) [9], which is aligned with its Nationally Determined Contributions (NDCs) under the Paris Agreement.

3.1 Projections and deployment in Chile

The PELP outlines three decarbonization scenarios for Chile: "Recovery", "Carbon Neutrality", and "Accelerated Transition" as shown in Figure 2. These scenarios reflect different paths the country could take towards achieving its decarbonization goals. In the "Carbon Neutrality " scenario, the focus is on significantly reducing GHG emissions by 2050, supported by a strong adoption of clean technologies, including an increased share of renewable energy sources like CSP. The " Accelerated Transition " scenario considers a faster transition with a more aggressive expansion of renewable technologies and earlier achievement of carbon neutrality [9], as shown in Figure 2.

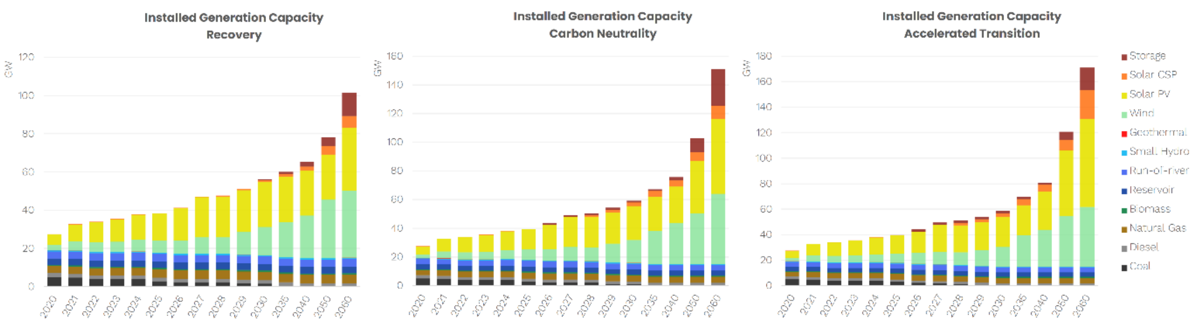

Figure 2. *Installed generation capacity in Chile under three decarbonization scenarios defined in PELP 2023-2027 [9].*

Chile has moved fast in the adoption of renewable energy in the energy matrix, however, while solar photovoltaic (PV) and wind power have seen rapid deployment due to their cost-effectiveness, they present challenges due to their intermittent nature. These technologies generate power independently of demand profiles, leading to grid instability and curtailment issues, particularly in regions like northern Chile, where the installed PV capacity exceeds the daytime electricity demand [10]. Moreover, the Chilean electricity market operates on a marginal cost regime, which exacerbates these issues by failing to provide sufficient incentives for energy storage solutions, such as batteries, which remain costly [11]. These challenges highlight the need for more stable and dispatchable renewable energy sources.

CSP technology offers a potential solution to the challenges posed by the intermittent generation of PV and wind power. CSP can provide baseload generation and is one of the most cost-effective options for large-scale energy storage, capable of storing thermal energy and dispatching it when needed [4], [12]. This makes CSP particularly valuable in sunny regions like northern Chile, which has the highest solar resource in the world [1]. CSP's ability to balance the fluctuating generation of PV and wind, and its potential to integrate with other technologies such as hydrogen production, underscores its key role in Chile’s energy transition. For this reason, CSP has been selected as a technological option in the future scenarios from the PELP 2023-2027 as shown in Figure 3.

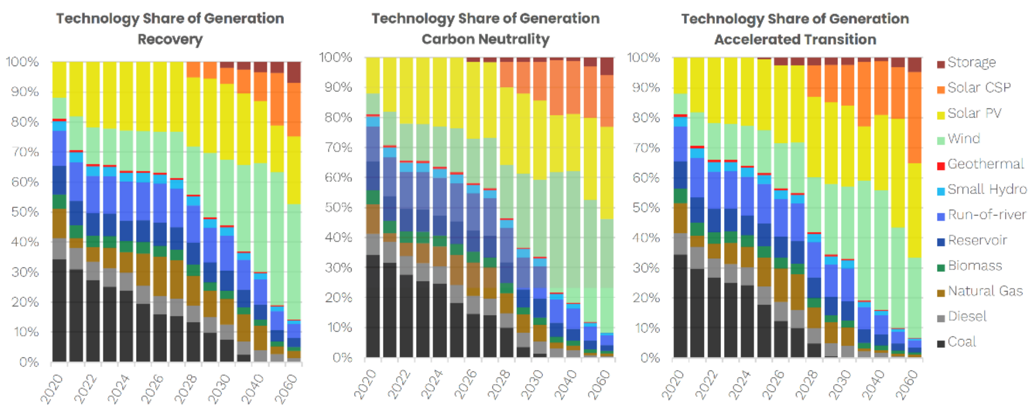

Figure 3. *Project technology share in generation for Chile under three decarbonization scenarios defined in PELP 2023-2027 [9].*

3.2 International projections and deployment

Globally, CSP deployment is expected to grow, driven by increasing recognition of its ability to provide stable, dispatchable power, but incentives and favorable policies are still required. The International Energy Agency (IEA) highlights in the Renewables 2023 that CSP and pumped storage hydropower have the highest shares of policy driven growth in 2023-2028 due to the high upfront investments and challenging business cases of both technologies [13]. In the case of CSP, growth comes entirely from competitive auctions in Morocco, the United Arab Emirate (UAE) and South Africa, most of which have state-backed financing to improve project bankability. The share of utility growth per technology based on market-driven or policy-driven is shown in Figure 4, alongside with the main rivers according to the IEA study [13].

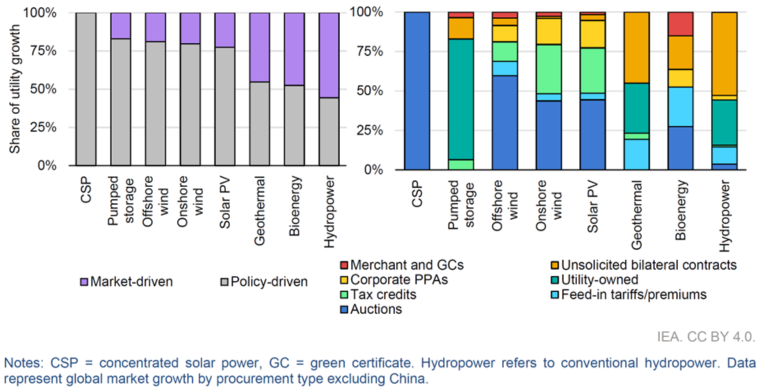

Figure 4. *Renewable electricity capacity by technology and primary driver (excluding China) for 2023-2028 [13].*

According to the IRENA World Energy Outlook 2023 [14], the power sector is one of the largest contributors to global emissions, accounting for 40% of CO_2 emissions in 2022. Decarbonizing this sector is therefore critical to meeting international environmental goals. Electrification is a key enabler of power sector decarbonization, and under the Planned Energy Scenario (PES) defined by IRENA, it is expected that renewable energy capacity will expand to 6 733 GW by 2030 and 15 835 GW by 2050. This expansion would increase the share of renewables in power generation from 28% in 2020 to 46% by 2030, and over 70% by 2050. However, the PES falls short of the requirements to limit global temperature rise to 1.5°C. According to IRENA's 1.5°C Scenario, total installed renewable generation capacity would need to increase to 11 173 GW by 2030 and 33 216 GW by 2050, as shown in Figure 5. This would require an average annual addition of approximately 1 000 GW of renewable energy capacity in the current decade—more than three times the renewable capacity added in 2022—and nearly 1 100 GW annually through 2050. CSP technology plays a significant role in achieving these targets under the IRENA's 1.5°C Scenario. Notably, the Levelized Cost of Energy (LCoE) for CSP has decreased by 68% between 2010 and 2021, reflecting the overall trend of cost reductions across renewable energy technologies.

To stay on the 1.5°C pathway, annual investments would need to increase significantly. Specifically, for CSP, the required investment would need to surge from a historical average of 1 billion USD annually to approximately 89 billion USD per year under the 1.5°C Scenario, as illustrated in Figure 5.

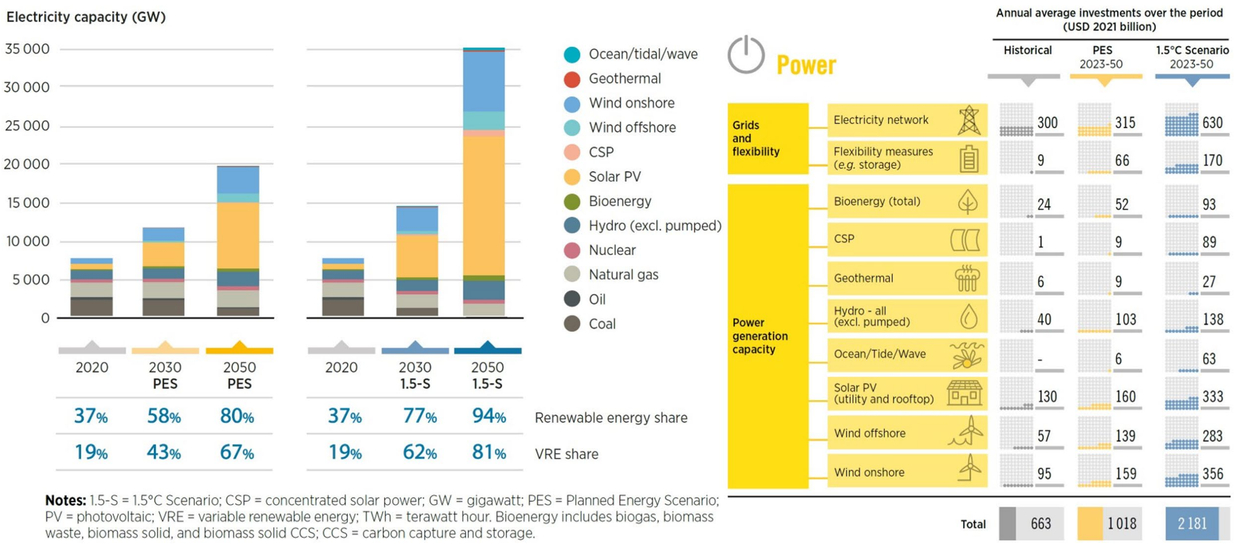

Figure 5. *Electricity capacity growth worldwide under the PES and 1.5°C scenarios for 2023-2050 (Left). Required average annual investments under the PES and 1.5°C scenarios for 2023-2050 (Right) [14].*

3.3 Strategies and Challenges for the Commercial-Scale Development of the CSP Industry

Scaling up CSP deployment to meet global energy targets requires overcoming several significant challenges. The CSP industry is currently in a critical transition from the formative to the growth phase, heavily relying on policy support schemes to drive expansion [15]. Historically, national policies have played a pivotal role in CSP deployment, exemplified by Spain's feed-in-tariff (FiT) scheme implemented between 2007 and 2013. This policy provided a guaranteed price for electricity generated from CSP, which encouraged rapid growth by attracting significant investment. However, the scheme also had drawbacks, such as high initial tariffs that eventually led to unsustainable costs and subsequent regulatory changes, including retroactive cuts and the imposition of taxes, which halted further development [4].

Technologically, the CSP landscape is still evolving, with no dominant design or configuration. Current technologies include parabolic troughs, central receiver systems, and emerging 3rd CSP systems designed to operate at higher temperatures to improve efficiency and reduce costs. These next-generation CSP technologies aim to operate above 700°C and employ alternative heat transfer fluids and materials, moving beyond molten salts, which are unsuitable at such high temperatures [16]. While these advanced systems hold promise for significant performance improvements and lower LCoE, they remain in early development stages and are not yet commercially widespread.

In parallel, commercial-scale CSP systems using molten salt storage continue to face technical challenges. One of the most pressing issues is the failure of molten salt tanks. For instance, failures in stainless steel 347H tanks in current central receiver plants have been attributed to high residual stresses after welding, non-uniform thermal expansion, and stress relaxation cracking. These issues can reduce the operational lifespan of the tanks to less than three years under certain conditions [17]. Addressing these failures is criticalfor enhancing the reliability of today's TES systems, which are fundamental to the dispatchability and cost-effectiveness of CSP plants.

Successful CSP deployment at a commercial scale in various countries offers valuable insights into effective policy and development strategies. Spain's FiT scheme, while initially successful, underscores the need for balanced and sustainable support mechanisms to avoid market distortions. On the other hand, Morocco and the UAE have successfully utilized public-private partnerships and international financing to build large-scale CSP plants. In Morocco, the Moroccan Agency for Sustainable Energy (MASEN) has played a central role in coordinating site selection, conducting pre-feasibility studies, and securing financing, leading to the successful deployment of the Noor Ouarzazate complex. This integrated approach has reduced development costs and attracted reputable international partners, setting a benchmark for future CSP projects [18].

China, which has emerged as the global leader in CSP development, presents a unique case study in rapid capacity expansion. The country's growth in CSP capacity has been driven by a comprehensive and aggressive policy framework that includes special tenders, substantial financial incentives, and significant investments in domestic manufacturing capabilities. Beginning with its 13th Five-Year Plan, China implemented a national FiT program specifically for CSP, which set ambitious targets for CSP capacity [19]. This program was complemented by government-backed subsidies and favorable tariffs, which were instrumental in making CSP projects financially viable.

Moreover, China has leveraged its robust manufacturing base to drive down the costs of CSP technology, making it more competitive on a global scale. Recent CSP projects in China, such as the 150 MW central receiver system (CRS) plants with thermal energy storage, have achieved some of the lowest capital costs worldwide, ranging from $4 761 to $5 713 USD/kWe. These projects have also demonstrated the ability to integrate substantial thermal energy storage, allowing for more than 8 hours of storage capacity, which enhances the dispatchability and economic viability of CSP plants [19].

China's approach also includes significant investments in research and development (R&D) aimed at overcoming technical challenges and improving the efficiency of CSP technologies. This focus on innovation has led to advancements in key components such as solar receivers and thermal storage systems, which are crucial for reducing the LCoE and enhancing the overall performance of CSP plants. The country's strategy of combining large-scale deployment with continuous technological innovation has positioned China as a critical player in the global CSP market [19].

As a result of these comprehensive efforts, China has not only led the way in CSP capacity expansion but has also set the stage for future growth by establishing a solid foundation of policy support, financial incentives, and technological innovation. This integrated approach has made China a benchmark for other countries seeking to develop their own CSP industries.

4. Results

The stakeholder interviews and literature review conducted in this work revealed several critical insights into the challenges and opportunities for CSP deployment in Chile. Key findings include:

- **Technological mistrust and regulatory barriers:**

Stakeholders in Chile expressed significant concerns regarding the reliability and long-term performance of CSP technologies, particularly related to the challenges in TES. The failure of molten salt tanks, as observed in international CSP projects, was highlighted as a major technical risk. This mistrust is further compounded by an incomplete regulatory framework in Chile, which creates uncertainties around the potential revenues from energy storage systems. The current regulatory environment lacks clear guidelines on the integration of TES systems within the national grid, leading to hesitancy among investors [3] [12].

- **Cost trends and financial viability:**

The study observed a notable decline in CSP technology costs, with capital expenditures (CAPEX) for CSP plants decreasing from $5 300 to $3 300 USD/kWe over recent years. This trend aligns with global cost reductions in CSP technologies, driven by advancements in manufacturing and scaling effects, and with the projections of the Ministry of Energy in Chile [20]. The interviews also highlighted the potential for further cost reductions driven by improved efficiency, particularly through technological advancements from countries like China, which is expected to lead to a "boom" in CSP development. However, stakeholders emphasized that further cost reductions are necessary to enhance the financial viability of CSP projects in Chile. The decreasing LCoE for CSP, which has dropped by 68% from 2010 to 2021, reflects these advancements but still requires additional policy support to be competitive against other renewable technologies such as PV and wind power.

- **Anticipated future technologies:**

The interviews revealed an expectation among stakeholders that a diverse mix of technologies, including CSP and batteries, will dominate the future energy landscape in Chile. This technology mix is considered essential to meet the country's energy storage and grid stability needs, given the increasing penetration of variable renewable energy sources. Stakeholders emphasized the importance of CSP as a key component in this mix due to its inherent storage capabilities and potential to provide stable, dispatchable power [3].

- **Regulatory and business model innovations**

Stakeholders highlighted the need for regulatory reforms to facilitate the growth of CSP and energy storage systems in Chile. They identified several critical areas for improvement, including [3]: The development of clear guidelines for the coordination and dispatch of energy storage systems, which are currently lacking; The creation of a regulation to define revenue streams for energy storage systems, particularly those providing capacity services; Addressing the disincentives in the current payment structure for energy storage systems with durations longer than five hours; and, introducing incentives for storage systems without direct subsidies, improving licensing conditions, and establishing a transitional period to determine revenue streams for energy storage systems.

- **Critical elements for future energy storage regulations**

Stakeholders also proposed specific elements to be included in future energy storage regulations. These include recognizing storage systems with durations exceeding five hours, revising auction bases to limit exposure to spot market risks, and implementing price discounts for energy storage systems. These elements are viewed as essential for unlocking the full potential of energy storage solutions in Chile, enabling them to contribute effectively to grid stability and flexibility [3].

- **Incentives and opportunities for CSP deployment**

To accelerate the development of large-scale energy storage systems, stakeholders identified several priority incentives, such as streamlining project permitting processes and utilizing storage systems to alleviate transmission constraints. They also noted the potential for CSP to contribute to various applications, including desalination, hydrogen production, and heat generation, positioning CSP as a versatile solution for different energy needs [3].

- **Opportunities in transitioning existing renewable plants**

Finally, stakeholders recognized opportunities in retrofitting existing renewable energy plants with storage capabilities to enhance grid reliability. They pointed out the need for energy storage systems to manage transmission congestion and facilitate energy arbitrage, although financial uncertainties pose challenges for smaller companies in accessing these opportunities [3].

Based on the analysis of stakeholder interviews, a summary of the main concerns, perceived barriers, and potential opportunities related to CSP deployment in Chile is presented in Table 1. This table aims to consolidate the qualitative insights into a concise and structured format for improved readability and interpretation.

Table 1. *Summary of key stakeholder insights and concerns regarding CSP deployment in Chile*

Key Area	Stakeholder insights and concerns
Technological mistrust & TES failures	Concerns about reliability and lifespan of molten salt tanks; need for improved thermal storage systems.
Regulatory uncertainty	Lack of clear rules for integrating TES into the grid; uncertain revenue streams deter investment.
Cost trends & financial viability	CAPEX is decreasing but still high; further reductions needed to compete with PV/wind; need for policy support.
Future energy mix	CSP and batteries expected to play complementary roles in ensuring grid stability.
Needed regulatory reforms	Urgent need for coordination rules, pricing mechanisms, and incentives for long-duration storage.
Elements for new storage regulations	Include >5h storage systems, reduce spot market exposure, apply price discounts.
Incentives for CSP	Simplify permitting, promote CSP for desalination, hydrogen, and thermal energy.
Opportunities for retrofitting	Retrofitting existing renewables with storage is promising but challenging for small developers.

5. Discussion and conclusions

The findings highlight the significant potential of CSP technology to enhance Chile's renewable energy landscape. CSP can particularly help address the intermittency challenges posed by solar PV and wind power. However, to realize this potential, several critical barriers must be overcome, as identified through stakeholder interviews and the literature review. However, realizing this potential requires overcoming several critical barriers, as identified through stakeholder interviews and literature review.

- **Addressing technological and development risks:**

One of the primary challenges highlighted by stakeholders is the lack of confidence in CSP technology, which stems from both misinformation and real technical risks, such as the failures of molten salt tanks in TES systems. This mistrust is compounded by the high costs and long timelines associated with securing suitable land for CSP projects in Chile. To mitigate these risks, it is essential to invest in further R&D to improve the reliability and efficiency of TES systems. Enhanced R&D efforts should focus on identifying and resolving the technical issues that lead to molten salt tank failures, thereby reducing the perceived risks and building trust in the technology among investors and developers.

- **The role of cost reductions and market evolution:**

The study reveals an optimistic outlook among stakeholders regarding the reduction of CSP technology costs. The recent decline in CAPEX for CSP plants, from \$5 300 to \$3 300 USD/kWe, indicates progress towards making CSP more competitive. However, further cost reductions are necessary to ensure CSP's financial viability. Technological advancements from countries like China, particularly in improving plant efficiency, are expected to contribute significantly to future cost declines. Chile should closely monitor these global developments and leverage international expertise to achieve similar cost reductions domestically.

- **Regulatory reforms and business model innovation:**

The results indicate that a key barrier to CSP deployment in Chile is the current regulatory framework, which lacks clarity and adequate incentives for the integration and operation of energy storage systems. To support the large-scale adoption of CSP, Chile must introduce comprehensive regulatory reforms that provide clear guidelines for energy storage coordination, establish robust revenue models for storage services, and create incentives that promote longer-duration storage systems. These reforms should be designed to foster innovation without resorting to direct subsidies, ensuring a sustainable market environment that encourages private investment and reduces the reliance on public funds.

- **Strategic incentives and future opportunities:**

The study highlights the importance of targeted incentives to accelerate the development of CSP and energy storage technologies in Chile. Streamlining project permitting processes, reducing bureaucratic barriers, and leveraging energy storage to address transmission constraints are critical steps. Additionally, CSP’s versatility in supporting applications such as hydrogen production, and heat generation offers opportunities to diversify its value proposition and enhance its attractiveness to investors. Developing a strategic framework that positions CSP as a multi-purpose energy solution will be crucial in maximizing its deployment potential.

- **Capitalizing on retrofitting opportunities:**

Chile has an opportunity to enhance grid stability by retrofitting existing renewable energy plants with energy storage capabilities. This strategy would enable better management of transmission congestion and support energy arbitrage, thereby improving grid reliability. However, overcoming financial uncertainties, particularly for smaller companies, will require targeted support mechanisms, such as low-interest loans or public-private partnerships, to facilitate the transition.

CSP technology holds considerable promise for contributing to Chile’s renewable energy transition, particularly in providing stable, dispatchable power that complements the increasing penetration of variable renewable energy sources like solar PV and wind. However, achieving its full potential requires addressing several key challenges, including technological reliability, regulatory clarity, and financial viability. By implementing targeted regulatory reforms, fostering innovation through enhanced R&D support, and developing strategic incentives for both CSP and energy storage technologies, Chile can build a robust CSP industry that supports its decarbonization goals and ensures energy security.

In conclusion, this study provides a strategic framework for addressing the key barriers to CSP deployment in Chile, drawing on both local insights and international best practices. By systematically addressing these challenges, CSP has the potential to become a pivotal component of Chile’s sustainable energy transition, enhancing grid resilience and reliability. Prompt and coordinated efforts are essential to ensure that Chile achieves its energy security objectives and meets its ambitious decarbonization targets.

Data availability statement

There is no relevant additional data to this article beyond the presented content.

Author contributions

Conceptualization, C.F., investigation, C.F., methodology C.F., writing – original draft C.F. and F.M., writing & editing, C.F and F.M., review & supervision F.D. and M.C.

Competing interests

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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