

Techno-Economic Analysis of a Solar Calcliner for CO₂ Emissions Reduction in the Chilean Cement Industry

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Abstract. Clinker, constituting approximately 72% of cement's composition, is produced through an energy-intensive process that significantly contributes to CO₂ emissions. This study explores the integration of a solar calciner into the Chilean cement industry, particularly in the Antofagasta region, which is characterized by high solar energy irradiation, with an annual DNI of 3,250 kWh/m². This region also accounts for approximately 30% of the country's cement sector energy consumption. In this context, this study evaluates two Concentrated Solar Thermal (CST) scenarios: the Top of Tower (TT) system and the Beam-down (BD) system, assessing their technical and economic feasibility for reducing CO₂ emissions in the calcination process. The findings suggest that both CST systems could substantially reduce CO₂ emissions in the calciner. However, economic feasibility remains a challenge, primarily due to the low cost of coal, which is the main fuel in the Chilean cement industry. Additionally, the efficiency of the solar calciner is found to be crucial for achieving maximum emission reductions, for the scalability of the technology, and for its future adoption in Chile's cement industry. Although the Levelized Cost of Heat (LCOH) for the proposed plants is currently higher than the coal-fired calciners in which is produced about 90% of current clinker production in Chile, potential reductions in heliostat costs, coupled with an increase in carbon taxes beyond the current value of 5 USD/t_{CO₂}, could significantly improve the economic viability of CST plants in Chile's cement industry.

Keywords: Cement Industry, Integration of Solar Calcliner, Economic Analysis

1. Introduction

Concrete is a fundamental material in modern construction, forming the foundation for buildings, infrastructure, and urban development. Its widespread use is due to its versatility, strength, and durability, making it an ideal choice for a wide range of construction projects [1]. However, the increasing global demand for concrete, driven

by rapid urbanization and infrastructure growth, especially in developing regions, raises significant concerns about the environmental impact of cement production. Notably, the cement industry is currently one of the major sources of CO₂ emissions, accounting for nearly 8% of global emissions, which significantly contributes to climate change [2]. Consequently, reducing the carbon footprint of cement production has become a critical priority. Achieving net-zero emissions by 2050 is an ambitious target that requires a comprehensive approach and innovative solutions [3].

In this context, the Instituto del Cemento y del Hormigón de Chile (ICH) aims to reduce CO₂ emissions in Chile's cement industry by 15% by 2030, from the current level of 839 kg_{CO₂}/t_{clinker}. Their strategy involves integrating the co-processing of alternative fuels, enhancing energy efficiency, and reducing the clinker content in cement [4]. Additionally, leveraging solar energy presents a promising opportunity for further reducing CO₂ emissions, given Chile's high DNI levels. As illustrated in Figure 1, regions with cement manufacturing operations such as Antofagasta, Santiago, and Valparaíso experience high annual solar irradiance levels, ranging from 2,200 kWh/m² in the metropolitan region to as much as 3,250 kWh/m² in the northern region.



Figure 1. Annual direct normal irradiation in Chile [5]

Given this high solar potential, this study aims to analyze and compare two solar technologies for reducing CO₂ emissions in the cement calcination process: (I) the Top of Tower (TT) and (II) the Beam-Down (BD) systems. To date, no comparative analysis of these systems has been conducted within the context of the Chilean cement industry. By addressing this gap, the study provides a comprehensive evaluation of both systems from economic and technical perspectives.

2. Methodology

The technical analysis of the calciner combines design and yield assessment using the Monte Carlo ray-tracing software Solstice, along with a mathematical model for

heat integration into the cement production process. As shown in Figure 2, a thermal energy balance is performed for the solar calciner, considering various energy inputs and outputs, to determine the reduction in fuel consumption resulting from the solar calciner integration. A comprehensive technical and economic analysis is conducted to evaluate the impact of key parameters on the feasibility of the proposed scenarios. Various factors, such as solar field size, solar calciner efficiency, and thermal energy storage capacity, are evaluated to determine their impact on the annual thermal performance of the proposed plants.

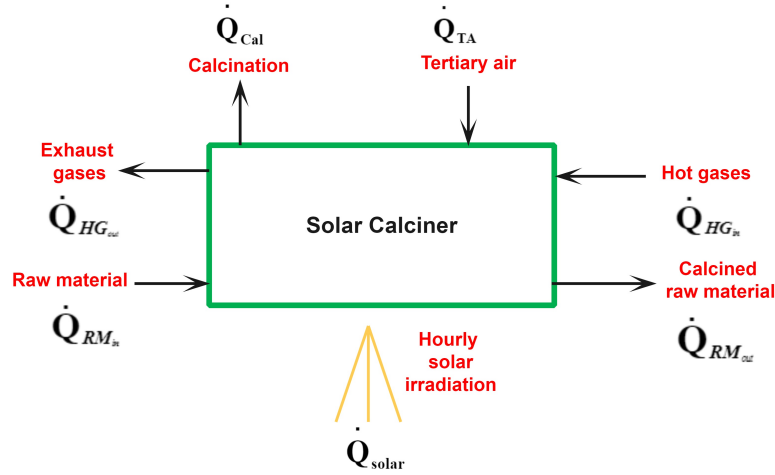


Figure 2. Schematic representation of the thermal energy balance in the solar calciner

Thus, the heat balance in the solar calciner can be determined by Eq. 1:

$$\dot{Q}_{RM,in} + \dot{Q}_{HG} + \dot{Q}_{solar} + \dot{Q}_{TA} = \dot{Q}_{FG} + \dot{Q}_{cal} + \dot{Q}_{RM,out} \quad (1)$$

Where $\dot{Q}_{RM,in/out}$ is the raw material energy at inlet and outlet, $\dot{Q}_{HG}$ is the hot gases energy from the rotary kiln, $\dot{Q}_{solar}$ is the solar energy entering into the solar calciner, $\dot{Q}_{FG}$ is the energy from the exhaust gases produced in the calciner, $\dot{Q}_{cal}$ is the energy required for the calcination, and $\dot{Q}_{TA}$ is the energy of the tertiary air from the clinker cooler. The calculation of the enthalpy for the hot gases and the raw material is calculated by Eq. 2:

$$\Delta \bar{h}_i = \int_{T_1}^{T_2} C_p(T) \cdot dT \quad (2)$$

The specific heat as function of temperature is taken from the data base of the National Institute of Standards and Technology (NIST) of the US Department of Commerce [6]. Concerning the calcination energy ($\dot{Q}_{cal}$), it is calculated by Eq. 3:

$$\dot{Q}_{cal} = \dot{m}_{RM} \cdot Y_{CaCO_3} \cdot \Delta H_{calci}^{\circ} \cdot (X_{out}^{dc} - X_{in}^{dc}) \quad (3)$$

Where $\dot{m}_{RM}$ is the raw material mass flow, Y_{CaCO_3} is the mass fraction of $CaCO_3$ in the raw material, $X_{out/in}^{dc}$ is the degree of calcination at the calciner outlet and inlet, respectively. $\dot{Q}_{solar}$ is the heat input into the solar calciner which is defined as:

$$\dot{Q}_{solar} = \dot{Q}_{SF} \cdot \eta_{th} \quad (4)$$

$\dot{Q}_{SF}$ is the hourly heat obtained from the solar field which is calculated in Solstice ray-tracing software which is a computational software based on the Monte Carlo method and η_{th} is the solar calciner efficiency. Therefore, the energy balance is considered is hourly resolution as well. Regarding the Solarization Rate (SR), it is calculated by Eq. 5:

$$SR = \left(1 - \frac{\sum \dot{Q}_{fuel}}{\sum \dot{Q}_{conv}} \right) \quad (5)$$

Here, $\dot{Q}_{fuel}$ represents the annual fuel consumption in the solar calciner, and $\dot{Q}_{conv}$ represents the annual fuel consumption in the conventional calciner.

A detailed economic assessment is also carried out to evaluate the viability of integrating solar calcination systems into the cement industry. In this context, capital expenditures (CAPEX) refer to the initial investment required for the deployment of the solar plant, encompassing the Thermal Energy Storage (TES) system, heliostat field, solar tower, Compound Parabolic Concentrator (CPC), and the solar calciner itself. Thus, TES costs are estimated at 9.7 USD/kWh, based in part on molten salt storage systems [7], with adaptations to the specific concept. Since the calciner raw material is stored directly, no additional storage medium is required, and insulation costs are assumed to double due to high operating temperatures. Heliostat costs are assumed to be 96 USD/m², based on current market data [8]. The Total Tower Cost (TTC) is derived from the System Advisor Model (SAM), which uses NREL's Annual Technology Baseline (ATB). CPC and solar calciner costs are based on Gonzalez et al. [9] and Moumin et al. [10], who also assessed the potential deployment of solar calciners in the cement industry. Secondary concentrator costs are based on Schöttl et al. [11] research studies. Site preparation costs are assumed to be 0.5 USD/m² [8], and a 10% contingency on total direct costs is included to account for uncertainties. Indirect capital costs (ICC) are estimated at 22% of CAPEX, and operational expenditures (OPEX) are assumed to be 2% of total CAPEX [10]. For the coal reference case, a fuel cost of 79 USD/t is used, based on data from the Chilean National Commission of Energy [12]. It is important to highlight that cost estimation for components such as the CPC, solar calciner, and TES remains highly uncertain due to the limited commercial deployment of such systems, emphasizing the need for continued research and development.

The focus of the analysis is on the Levelized Cost of Heat (LCOH), comparing the LCOH from the solar plant ($LCOH_{SP}$), which includes only the costs associated with the solar system, to the LCOH from a hybrid plant configuration ($LCOH_{HP}$), which incorporates both solar and coal-related costs.

3. Detailed description of the proposed scenarios

3.1 Top of Tower system

The Top of Tower (TT) system is depicted in Figure 3 which is similar to the systems described in previous research by González and Flamant [9] and Moumin et al. [10]. The proposed CST plant is designed to produce clinker while reducing CO₂ emissions during the calcination process. The raw materials are first preheated and then transferred to the top of the solar calciner. Inside the solar calciner, the materials are exposed to intense solar radiation, as well as exhaust gases and hot air from both the rotary kiln and the clinker cooler, allowing them to reach the calcination temperature of about 900°C. A compound CPC at the top of the tower (entrance of the solar receiver) should be also considered in order to reach the high temperature required by the chemical reaction [9].

To ensure a continuous supply of clinker, some of the calcined material is stored in the TES system for being used when solar irradiation is insufficient. After calcination, the material is transferred to the rotary kiln for clinkerization and then rapidly cooled in the clinker cooler. The resulting hot air from the cooling process is redirected to the solar calciner as tertiary air and to the rotary kiln as secondary air.

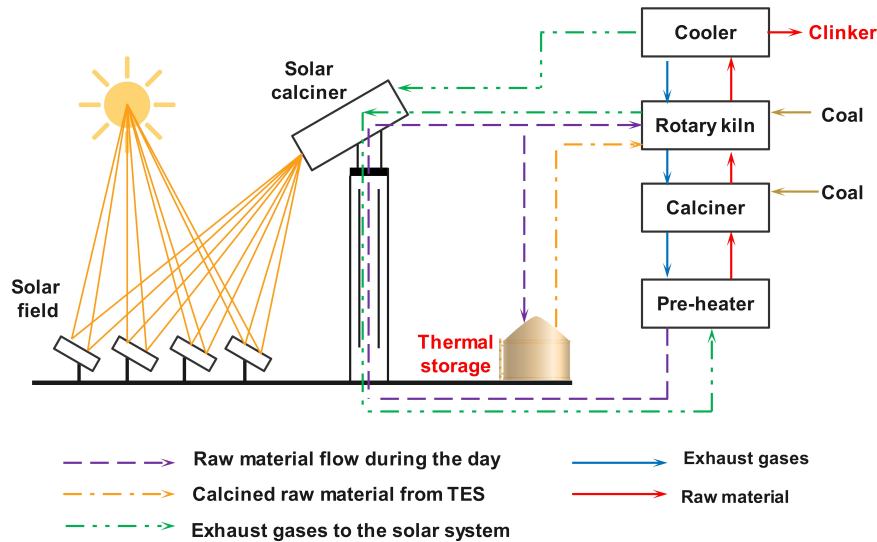


Figure 3. Schematic representation of top of tower system

3.2 Beam-down system

Transporting raw materials to the top of the tower at high temperatures is a significant challenge when integrating the Top of Tower (TT) system into the cement industry. Several solutions can address this issue, including traditional mine hoists, modern pneumatic conveyors, and Beam-Down solar concentrator systems. Specifically, using Beam-Down solar concentrators could offer substantial reductions in both CAPEX and OPEX for the transportation system and reducing the potential heat losses during the transfer of materials to the tower [9][13]. In this context, the Beam-Down (BD) system is proposed as a potential solution to these challenges, as depicted in Figure 4. In this configuration, the raw material is calcined in a ground-level solar reactor, which receives concentrated solar radiation from a secondary mirror that redirects the sunlight reflected by the heliostat field. Similar to the TT system, the required calcination temperature of 900 °C is achieved not only through solar input, but also with the assistance of exhaust gases from the rotary kiln and hot air from the clinker cooler.

4. Results

4.1 Technical potential of CO₂ reduction

For a more comprehensive understanding the influence of the solar field size quantified as Solar Multiple (SM) impacts potential CO₂ emission reduction in the solar calciner, Figure 5 compares both scenarios based on the solar field size and TES capacity. The graph indicates that increasing the SM reduces the difference in CO₂ emission reductions between the two scenarios. Although more complex optics due to the secondary reflector lead to higher optical losses, the advantages of a larger solar field in the BD scenario may compensate these losses. Generally, the maximum achievable CO₂ emission reduction is limited by both the SM and TES capacity. In particular, expanding the SM to 2.0

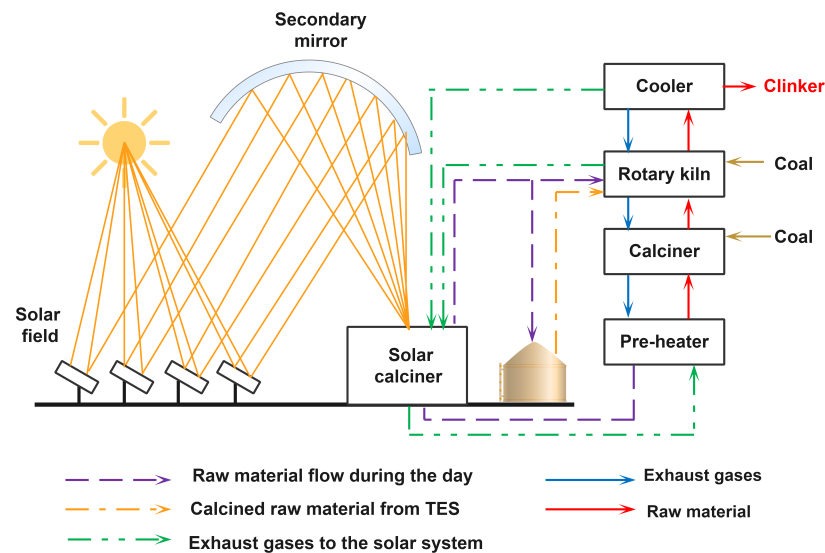


Figure 4. Schematic representation of Beam-down system

and increasing TES capacity to 16 – 20 hours significantly enhances CO₂ emission reductions, resulting in CO₂ reductions exceeding 70%. In contrast, further increasing the SM from 2.0 to 3.0 a 50% increase yields only marginal additional gains in CO₂ emissions reduction.

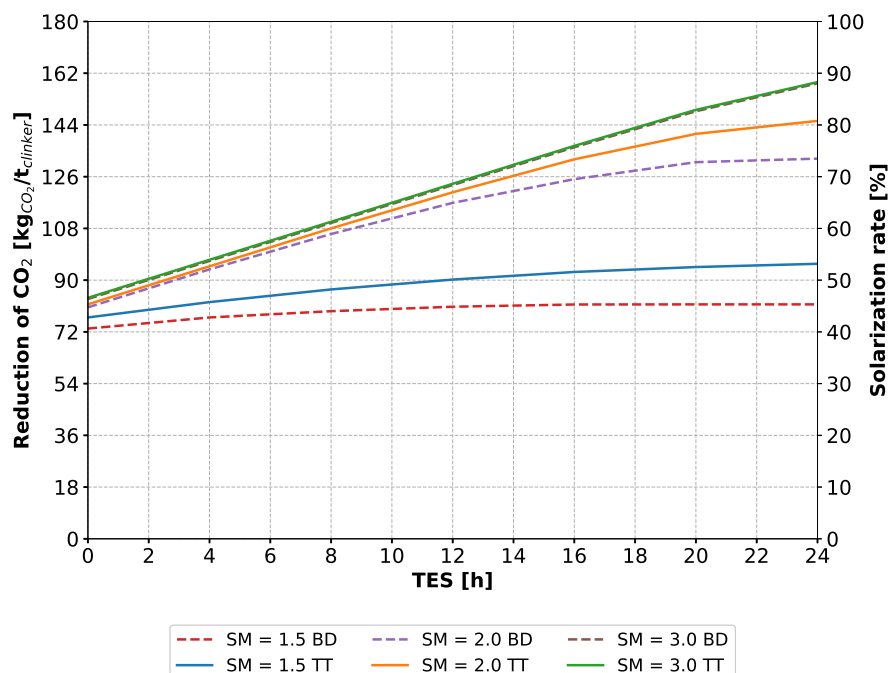


Figure 5. Comparison of the potential CO₂ reduction in the solar calciner depending on the size of the solar field and TES capacity

4.2 Influence of the solar calciner efficiency on the proposed plants

Solar calciner efficiency plays a key role in the potential reduction of CO₂ emissions in the proposed system. As shown in Figure 6, improvements in calciner efficiency directly enhance the specific CO₂ emissions reduction. In general, higher solar calciner thermal efficiency combined with greater TES capacity results in more substantial emission

reductions. Moreover, while increasing efficiency reduces the performance gap between the TT and BD configurations, expanding TES capacity tends to amplify the difference in their CO₂ reduction performance.

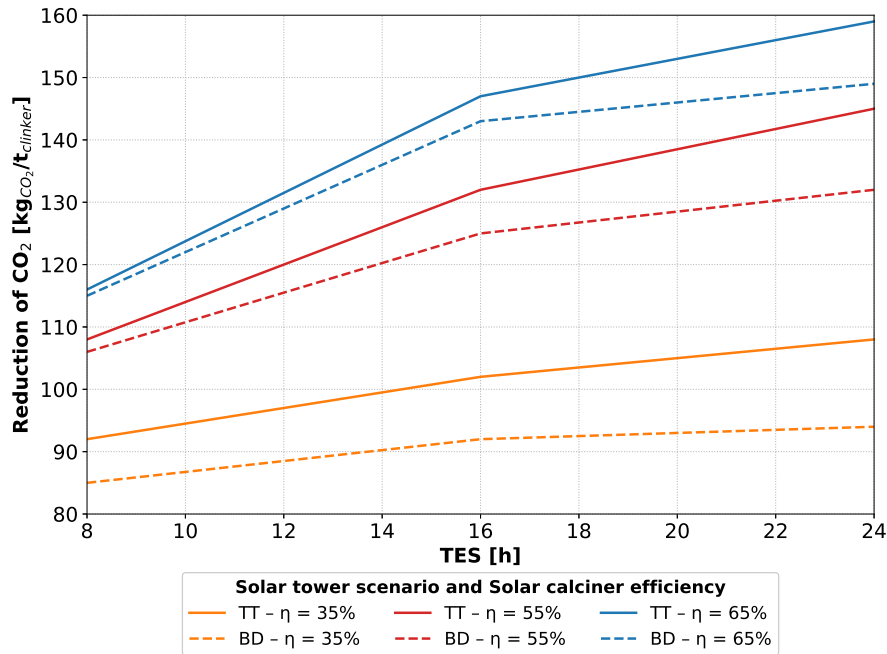


Figure 6. CO₂ Emissions Reduction as a Function of Solar Calciner Efficiency and TES Capacity (SM = 2.0)

4.3 Economic analysis

Regarding the economic feasibility of the proposed plants, Figure 7 displays various configurations and their corresponding LCOH ranges, which are calculated considering various factors such as solar field size and thermal storage capacity. These costs are compared to those of conventional coal and natural gas-fired calciners. The analysis shows that none of the solar configurations currently offer economic competitiveness compared to conventional coal-fired calciners, which are responsible for 93% of the fuel consumption in the Chilean cement industry [14]. It is observed that as the SM decreases, the LCOH declines. This is mainly due to the substantial impact of solar field costs on capital expenditure, indicating that the increased costs of expanding the solar plant outweigh the potential gains in energy production. The LCOH_{HP} decreases further at lower SM values due to the reduced solarization levels. This reduction is driven by the fact that the portion of energy not supplied by the CST system is covered by coal, which has a substantially lower LCOH. As a result, the overall cost of heat is significantly reduced. For example, Figure 5 shows that at an SM of 1.5, the solarization rate is limited to 50–60%, indicating that a considerable share of the thermal demand is still met by coal. Given the low cost of coal-based heat, the resulting LCOH_{HP} for the hybrid system is lower than that of systems operating with higher solar multiples.

Although CST technology has the potential to reduce CO₂ emissions, its economic viability remains a challenge due to Chile's low coal prices. However, anticipated reductions in heliostat costs and projected increases in carbon taxes rising from 5 to 75 USD/t_{CO₂} by 2030 according to the Paris Agreement could enhance the feasibility of CST plants.

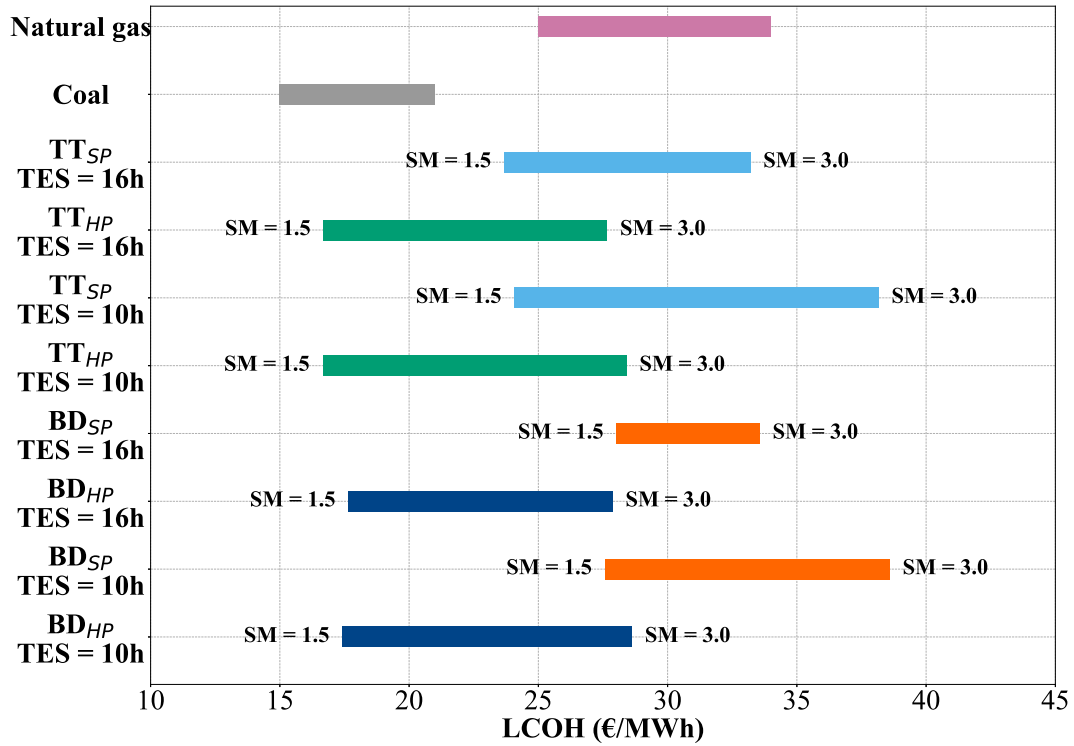


Figure 7. Comparison between the LCOH for the TT and BD proposed scenarios, coal and natural gas (Considering 5 USD/t_{CO₂} carbon taxes)

Compared to natural gas, which has a LCOH ranging from 25 to 34 €/MWh, CST could become more economically viable. Although natural gas currently accounts for only 4.2% of the Chilean cement sector's energy consumption [14], future increases in coal costs driven by its high CO₂ emissions may position natural gas as a more attractive alternative. This shift could promote the development of CST–natural gas hybrid systems, which would benefit from the lower CO₂ emissions associated with natural gas combustion. As CST technologies continue to advance and regulatory frameworks evolve, their integration into the Chilean cement industry could become feasible, offering a significant contribution to long-term CO₂ emissions reduction.

5. Conclusions and Outlook

This paper investigates the integration of CST plants into the Chilean cement industry to reduce CO₂ emissions during the calcination process. It evaluates two main designs: the Top of Tower and the Beam-Down systems. The analysis underscores that the size of the solar field plays a critical role in reducing CO₂ emissions. However, expanding the solar field beyond a SM of 2.0 does not lead to significant additional reductions in CO₂ emissions from the calciner. Additionally, economic feasibility diminishes due to high heliostat costs, which account for 35% of CAPEX. The LCOH for both the solar-only system (LCOH_{SP}) and the hybrid solar–fossil fuel system (LCOH_{HP}) currently exceeds that of conventional coal-fired calciners. However, with carbon taxes expected to rise significantly above the current level of 5 USD/t_{CO₂}, and with potential reductions in heliostat costs, CST systems could become increasingly feasible. Moreover, hybrid CST systems integrated with natural gas offer promising opportunities due to the lower CO₂ emissions associated with natural gas compared to coal. Ultimately, achieving an optimal balance between solar calciner efficiency, solar field size, TES capacity, and fuel type is essential to maximizing both emissions reduction and economic viability.

Future work should also focus on integrating Carbon Capture and Storage (CCS) technologies with CST systems to achieve substantial CO₂ emission reductions in cement production. Given that the calcination process alone contributes approximately 556 kg_{CO₂}/t_{clinker}, CCS could play a pivotal role in mitigating process emissions. Combining CST with CCS offers the potential to reduce fossil fuel dependence while supplying high-temperature renewable heat. Further investigation into the technical and economic feasibility of such integrated systems is essential to advancing the sustainability of Chile's cement industry.

Author contributions

Juan Sebastian Zuleta Marin [Conceptualization of this study, Methodology, Software, Data curation, Writing- original draft preparation, editing and Software], Gregor Bern [Methodology, Conceptualization of this study, results analysis, writing], Frank Dinter [Conceptualization of this study, results analysis], Werner Platzer [Methodology, Conceptualization of this study, results analysis, writing].

Competing interests

The authors declare no competing interests

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