Influence of CO_2 conditioning strategies on thermochemical energy storage performance in solar power towers

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Abstract

This work presents a dynamic and techno-economic analysis of a solar power tower plant integrated with a thermochemical energy storage system based on the calcium looping process and coupled with a supercritical CO_2 Brayton cycle. The study evaluates five alternative configurations of the CO_2 storage line, aiming to improve operational flexibility, reduce parasitic consumption, and enhance system efficiency. Dynamic simulations were performed in OpenModelica using real meteorological data from Carrera Pinto, Chile, with component models for compression, expansion, reheating, and hybrid thermal storage integration. The results demonstrate that the inclusion of molten salt and thermal oil subsystems significantly reduces auxiliary power demand and improves thermal management. Among all configurations, the thermal oil system achieved the best techno-economic performance, with a LCOE of 90.28 USD/MWh and a capacity factor of 65.1%. The findings confirm the potential of TCES-CaL integrated with sCO_2 Brayton cycles as a feasible pathway for next-generation dispatchable solar power plants.

Keywords: Calcium looping, supercritical CO_2 Brayton cycle, dynamic simulation, techno-economic analysis, renewable energy integration.

1. Introduction

The global transition toward a carbon-neutral energy system has intensified research efforts on renewable technologies capable of providing reliable and dispatchable power generation. While photovoltaic and wind systems dominate current renewable installations, their inherent intermittency highlights the need for complementary solutions that can ensure continuous energy supply. In this context, Concentrated Solar Power (CSP) stands out for its capability to integrate Thermal Energy Storage (TES), thereby enhancing grid stability and extending solar power utilization beyond daylight hours (Prieto et al., 2020).

Among CSP technologies, Solar Power Towers (SPT) offer the highest operating temperatures, often exceeding 700 °C, which enables superior thermodynamic efficiency when coupled with advanced power cycles such as the supercritical CO_2 (sCO_2) Brayton cycle (Arias et al., 2022; Shahabuddin et al., 2021). The continuous pursuit of higher temperatures has fostered the exploration of alternative storage media, with Thermochemical Energy Storage (TCES) based on the Calcium-Looping (CaL) cycle emerging as a particularly promising option. The reversible carbonation–calcination reaction of calcium oxide and calcium carbonate ($CaO + CO_2 \leftrightarrow CaCO_3$ + Heat, $\Delta h_{rx} = 178$ kJ/mol) allows efficient storage and release of heat at 700–1000 °C, achieving energy densities above 3 GJ/m³ while relying on abundant and low-cost materials such as limestone (Khan et al., 2025; Wu et al., 2024; Yang et al., 2021).

Although CaL-based TCES systems have demonstrated strong potential in laboratory and pilot-scale studies (Carro et al., 2021), their integration into large-scale SPT plants introduces significant engineering challenges. One of the most critical aspects lies in the CO_2 conditioning and circulation system, which must operate under wide variations of mass flow, temperature, and pressure throughout charging and discharging cycles. Conventional compression and cooling subsystems can account for more than 35 % of parasitic energy consumption, significantly affecting overall efficiency (Khan et al., 2025). Furthermore, most existing technoeconomic analyses have been conducted under steady-state conditions, thereby neglecting the dynamic behavior of the CO_2 loop under fluctuating solar input (Wang et al., 2025).

This study aims to fill this research gap by analyzing the impact of different CO_2 conditioning strategies on the

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performance of a CaL-based TCES integrated into an SPT plant. Using a dynamic simulation framework developed in Modelica and Python. The findings contribute to the understanding of how optimized CO_2 management can improve both the energetic and economic performance of next-generation CSP–TCES plants designed for high-temperature operation.

2. Methodology

The proposed solar power tower plant is illustrated in Figure 1, adapted from the reference configuration described in (Nieto et al., 2025). The system integrates a TCES-CaL unit with a sCO_2 Brayton cycle to achieve continuous and dispatchable power generation. The methodology adopted in this study combines optical design, thermochemical modeling, and dynamic simulation to evaluate the performance, flexibility, and techno-economic potential of the plant under realistic solar conditions.

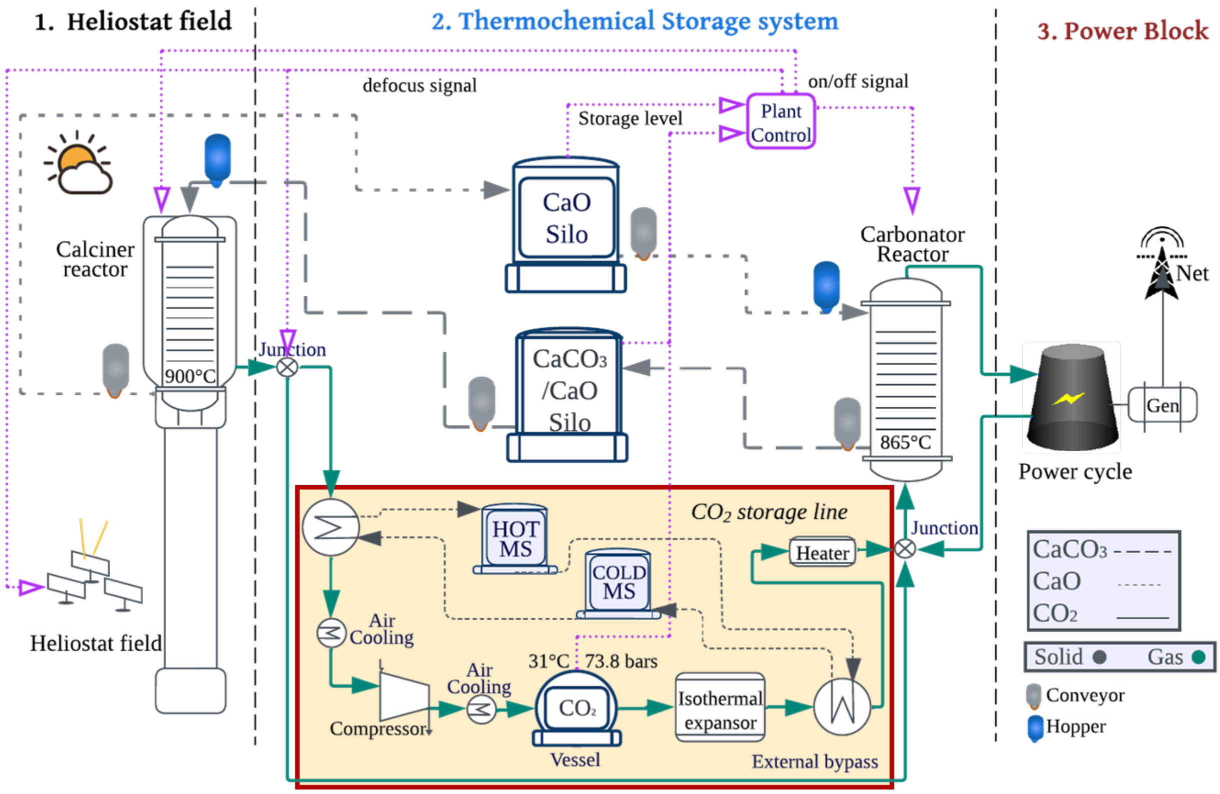

Figure 1: Conceptual design of the TCES–CaL solar power tower system.

2.1. Solar field and receiver design

The solar field is designed using SolarPILOT, employing a polar heliostat layout to minimize cosine and blocking losses while maximizing annual optical efficiency. The heliostat field focuses solar radiation onto a central receiver, which simultaneously functions as a solar calciner. This receiver is designed to operate at 850–950 °C, providing the heat required for the endothermic calcination reaction of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$). Commercial limestone is employed as both the heat transfer and reactive medium, taking advantage of its high availability and low cost.

2.2. CO_2 storage subsystem configuration

The CO_2 storage subsystem operates in two distinct modes: charging and discharging. During the charging phase, concentrated solar energy drives the calcination reaction at 850–950 °C, producing solid CaO and gaseous CO_2. The products are then stored separately: CaO in insulated silos at ambient temperature, and CO_2 in high-pressure vessels as a dense fluid. To minimize compression work, the CO_2 stream is first pre-cooled, then compressed in multiple stages, and finally stored under near-critical conditions. During the discharging phase, the exothermic carbonation reaction ($CaO + CO_2 \rightarrow CaCO_3$) occurs at 750–865 °C, releasing heat to drive the sCO_2 Brayton power cycle. The stored CO_2 is expanded, reheated, and fed to the carbonator, where it reacts with CaO to deliver high-grade thermal energy for power generation. This configuration enables the complete integration of the thermochemical cycle with the power block, ensuring high-temperature heat delivery and reduced dependency on auxiliary fossil sources.

New thermodynamic and control components were developed and integrated into the Modelica-based dynamic framework. The subsystem models were designed to ensure full thermodynamic consistency and operational flexibility under transient conditions, enabling a realistic representation of the TCES–CaL system coupled with the sCO_2 Brayton cycle. The CO_2 storage unit was modeled as a high-pressure vessel operating between 30 and 73.8 bar and at a temperature of 31 °C, where CO_2 is stored as a compressed gas. Its behavior was governed by mass and energy balance equations and represented as a compressible real gas using Helmholtz energy-based equations of state implemented through the CoolProp library. The compressor and expander models were semi-empirical, incorporating isentropic efficiency, pressure ratios, and cooling demands. In advanced configurations, the expander was replaced with a turbine model that recovers mechanical work during discharge, reducing parasitic losses. Electric heaters and coolers were implemented to regulate CO_2 temperature during compression and expansion, ensuring safe operation of the calciner, carbonator, and sCO_2 power block.

To explore hybrid configurations, two auxiliary thermal storage systems were incorporated. A molten salt storage loop (operating up to 550 °C) to support CO_2 cooling and reheating, thereby reducing electrical auxiliary consumption and enhancing thermal stability. A thermal oil storage unit (300–400 °C) to preheat CO_2 before turbine expansion, increasing thermal integration flexibility and recovery of low-grade heat. Additionally, external bypass valves were implemented as Boolean-controlled components, allowing dynamic flow redirection around compressors, expanders, or heat exchangers to minimize pressure drops and improve system stability. All subsystems were interconnected through standard Modelica fluid and thermal connectors, transferring mass flow, pressure, temperature, enthalpy, and heat rate. The CO_2 storage module was implemented as a single interchangeable component, where the five alternative configurations differ in compression, expansion, and reheating strategies but remain compatible with the global plant architecture.

The complete model was driven by hourly meteorological inputs (Direct Normal Irradiance (DNI), ambient temperature, and wind speed) representing a full operational year. The framework captured transient responses of all major components, enabling the computation of net power output, thermal efficiency, parasitic consumption, and dispatch capability. This system-level modeling approach provides a consistent basis for the comparative assessment of the five CO_2 storage line configurations, ensuring that performance differences arise solely from design variations rather than boundary or resource conditions.

2.3 Design modifications and alternative configurations

To enhance operational flexibility, thermal management, and overall system efficiency, the reference configuration was modified into five alternative layouts, each targeting a specific design improvement. The corresponding schematic diagrams are presented in Figure 2.

- Baseline: Consists of CO_2 cooling, multi-stage compression, storage vessel, isothermal expansion, and reheating stages.
- External bypass: Incorporates an external bypass line connecting the calciner directly to the carbonator, minimizing parasitic losses associated with CO_2 compression and storage.
- Molten salt storage: Integrates a molten salt thermal storage operating up to 550 °C, which serves as an intermediate heat transfer fluid during cooling and reheating.
- Turbine+preheater: Replaces the CO_2 expander with a dedicated turbine equipped with a preheater, optimizing the expansion process and increasing conversion efficiency.
- Thermal oil system: Adds a secondary thermal oil storage system that supports the preheater and recovers low-grade heat downstream of the turbine, further improving system efficiency and overall energy recovery.

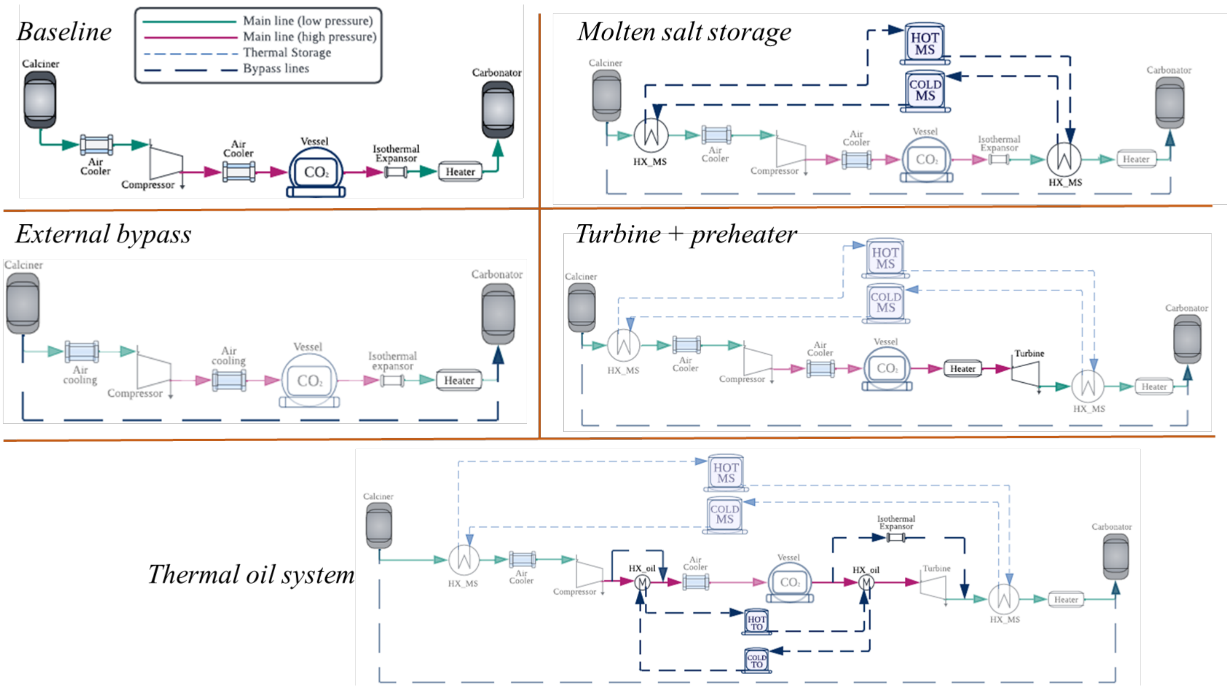

Figure 2: Proposed configurations of the CO_2 storage subsystem.

2.4 Dynamic modeling framework

A dynamic simulation model of the proposed hybrid plant was developed using the Modelica language, adopting a modular and component-based structure to facilitate scalability and comparison among the five alternative CO_2 storage configurations. Each physical and chemical subsystem—solar field, receiver, reactors, compressors, heat exchangers, and the sCO_2 Brayton cycle—was represented as an independent, reusable component. This modular structure enables consistent performance assessment while allowing rapid modification of the CO_2 storage subsystem. The model builds upon elements adapted from the SolarTherm library (de la Calle et al., 2018; Scott et al., 2017), including the solar resource, heliostat field, thermal components, and power block, which were modified to reflect the operational range of the CaL–TCES system. Custom reactor and CO_2 storage models were developed to simulate the transient interactions among calcination, carbonation, and CO_2 handling processes. These additions allow accurate prediction of mass flow, enthalpy, and temperature dynamics throughout the storage line.

Simulations were executed in OpenModelica 1.22, ensuring full compatibility with the Modelica Standard Library (MSL 4.0). Data exchange between subsystems was handled through fluid and thermal connectors, while control sequences were defined via logical interfaces to manage charging and discharging transitions.

The techno-economic assessment was conducted during post-processing using OMPython, estimating the annual energy output, plant efficiency, and Levelized Cost of Energy (LCOE) following the methodology of (Meybodi & Beath, 2016). The Levelized Cost of Storage (LCOS) was computed according to (Rodríguez-Pastor et al., 2024). This unified evaluation framework enables direct benchmarking of the alternative configurations under equivalent boundary conditions, providing insight into performance–cost trade-offs and optimization potential for large-scale CaL–TCES deployment.

3. Results and discussion

3.1 Dynamic behavior and operational transitions

Annual simulations were performed using typical meteorological data from Carrera Pinto, Chile, to assess the performance of the proposed CO_2 storage line configurations. Each configuration included subsystem components such as the compressor, expander/turbine, electric heater, cooler, molten salt loop, thermal oil loop, and bypass options (internal and external) modeled as independent units and integrated into the main vessel block. Figure 3 illustrates the short-term dynamic behavior of the complete system over a representative operating period.

Figure 3a shows the evolution of the CO_2 storage level, highlighting the transitions between charging, defocusing, and discharging modes. Under high solar irradiance, the storage reaches its maximum capacity, triggering the defocus control strategy to prevent overcharging. Figure 3b presents the instantaneous power and heat flow profiles, including the solar input to the receiver, the projected thermal load, and the net electrical output. The results confirm that CO_2 compression represents a major parasitic load during charging, reducing net plant output.

A comparative analysis among the five configurations reveals clear distinctions. The external bypass (red) effectively reduces compression costs during defocus periods. The molten salt storage (purple) minimizes heater consumption in discharge mode. The turbine + preheater (green) configuration is non-viable, as turbine gains are offset by the preheater's energy demand. The thermal oil system (grey) eliminates the need for an auxiliary preheater, enhancing turbine performance during both charging and discharging.

Figure 3c presents the weekly energy balance of the plant. The main energy losses originate from optical effects, followed by thermal losses in the power block. Parasitic consumption, mainly associated with the CO_2 storage line, remains significant but decreases notably in hybrid configurations that incorporate molten salt or thermal oil loops. These systems improve energy recovery, resulting in a measurable increase in overall plant efficiency.

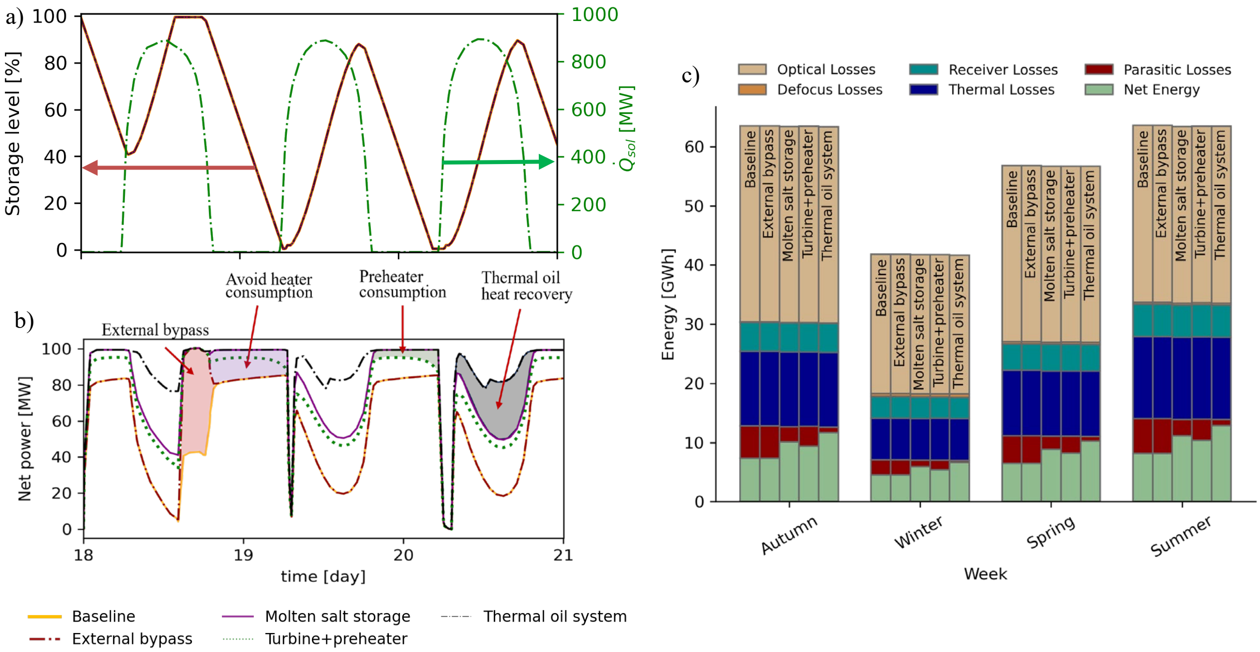

Figure 3: Simulation results: (a) CO_2 storage level and solar heat input ($\dot{Q}_{sol}$), (b) net power output, and (c) weekly energy distribution over the representative operating season.

3.2 Annual energy performance

The annual performance indicators for the five CO_2 storage line configurations are presented in Figure 4. The hybrid configurations (molten salt and thermal oil systems) achieved the lowest energy losses, reducing them by 57.1% and 66.7% compared with the baseline, respectively. These same options also deliver the highest capacity factors, reaching 59.8% for molten salt and 65.1% for thermal oil. However, final design selection must also consider the economic implications, addressed in the following subsection.

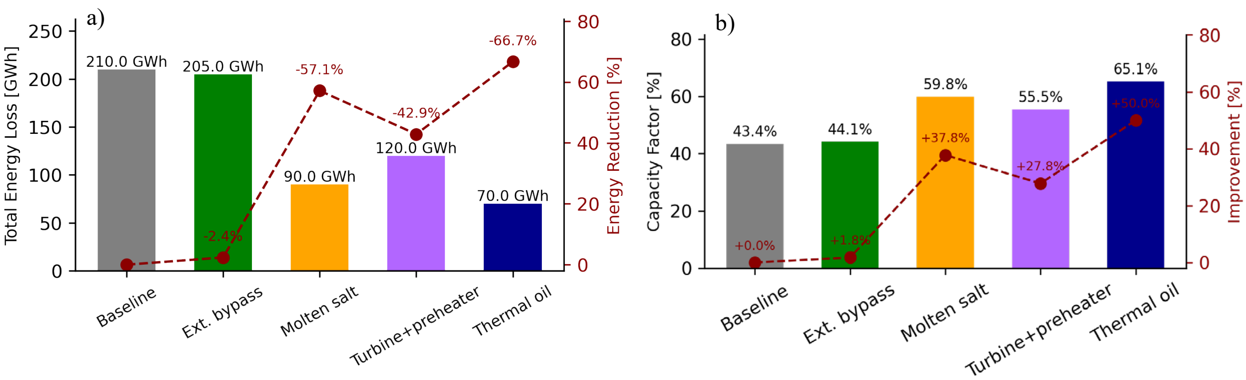

Figure 4: Annual energy performance indicators: (a) total energy losses and (b) capacity factor for each CO_2 storage configuration.

3.3 Techno-economic analysis

Figure 5a displays the plant cost distribution for each configuration under SM = 2.1 and STO = 12 h conditions. The CO_2 line itself contributes modestly to total plant cost but plays a major role in operational performance, as reflected in the LCOE and LCOS summarized in Table 1. Figure 5b details the cost breakdown within the CO_2 line, showing that hybrid systems with thermal storage eliminate electric heaters and their associated capital costs. The highest costs correspond to the compressor, turbine, and heaters, while the molten salt configuration yields the lowest total cost, followed by the thermal oil system. Even in the most complex layout, the total cost of the CO_2 line remains below 12 million USD.

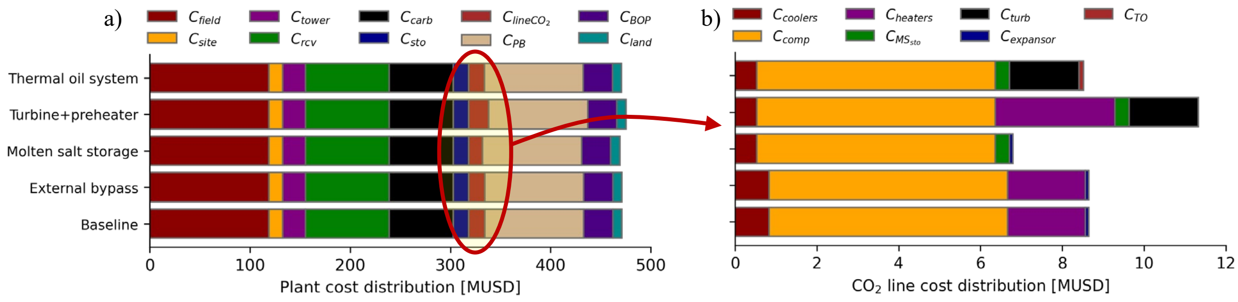

Figure 5: Cost distribution for each configuration: (a) total plant cost and (b) CO_2 storage subsystem cost breakdown.

3.4 Key Performance indicators

A comparative summary of Key Performance Indicators (KPIs) is provided in Table 1, where the baseline case represents the simple vessel configuration and successive cases include progressive subsystems (bypass, molten salt, turbine + preheater, thermal oil). The results highlight the significant performance enhancement achieved through thermal integration and parasitic loss mitigation.

Table 1: Comparative techno-economic performance of alternative CO_2 storage line configurations.

Configuration	Capacity factor [%]	LCOE [USD/MWh]	LCOS [USD/MWh]	$C_{CO_2\ line}$ [MUSD]	Improvement [%]
Baseline	43.42	135.53	23.18	15.98	-
External bypass	44.15	133.27	22.80	15.98	+1.75
Molten salt storage	59.82	97.91	16.44	13.79	+37.80
Turbine + preheater	55.48	106.97	18.89	19.93	+27.80
Thermal oil system	65.12	90.28	15.38	15.52	+50.02

The bypass configurations increase operational flexibility under variable solar input, while the turbine integration partially recovers compression work, lowering auxiliary consumption. The molten salt and thermal oil systems exhibit the most favorable techno-economic trade-off due to the substantial reduction in heater energy consumption, which significantly enhances overall plant efficiency while lowering both the LCOE and the LCOS. from 135.53 and 23.18 USD/MWh in the baseline configuration to 90.28 and 15.38 USD/MWh, respectively, for the thermal oil system. Despite the additional system complexity introduced by these hybrid configurations, the total CO_2 line cost ($C_{CO_2\ line}$) remains relatively unchanged between baseline and thermal oil system configuration. Among all alternatives, the thermal oil system stands out as the most competitive option, achieving an overall performance improvement of approximately 50% compared to the baseline. A summary of the main abbreviations used in this study is provided in Appendix A.

4. Conclusions

This work presented a dynamic and techno-economic assessment of a solar power tower plant integrated with a TCES system based on the CaL process and coupled with a supercritical CO_2 Brayton cycle. The study focused on the development and evaluation of five alternative CO_2 storage line configurations, designed to enhance operational flexibility, reduce parasitic consumption, and improve overall plant efficiency under real solar conditions.

Annual simulations were carried out using meteorological data from Carrera Pinto, Chile, employing a dynamic modeling framework developed in Modelica. The proposed approach enabled the accurate representation of transient interactions between the solar receiver, thermochemical reactors, and the CO_2 storage subsystem. The results demonstrated that the CO_2 line configuration significantly influences plant performance, both in terms of energy efficiency and economic competitiveness.

The findings showed that bypass configurations improve flexibility during variable solar irradiance and mitigate overcharging during peak radiation periods. The integration of a turbine partially recovers compression work, although its benefit is limited when additional preheating is required. In contrast, hybrid thermal storage systems based on molten salts and thermal oils substantially enhance thermal integration and reduce parasitic losses. Among all analyzed configurations, the thermal oil system demonstrated the best overall performance, achieving the highest capacity factor (65.12%) and the lowest LCOE (90.28 USD/MWh), while maintaining a moderately similar CO_2 line cost ($C_{CO_2\ line}$= 15.52 USD/MWh). This represents an overall improvement of approximately 50% compared to the baseline layout. The thermal oil configuration effectively balances efficiency, cost, and operational stability, making it the most promising option for large-scale implementation.

Future work will extend this research by incorporating multi-objective optimization to refine the CO_2 line control strategy and evaluating the influence of solar multiple and storage capacity on system performance. Additionally, experimental validation of the hybrid configurations will be pursued to strengthen the practical feasibility of the proposed concept. Overall, the results confirm that the integration of CaL-based TCES systems with sCO_2 Brayton cycles represents a technically viable and economically competitive pathway toward dispatchable next-generation solar power plants.

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Appendix A: Nomenclature

This appendix summarizes the nomenclature and abbreviations used throughout the manuscript.

Table A1: List of abbreviations and their corresponding definitions.

Name	Abbreviation
Concentrated solar plant	*CSP*
Thermal energy storage	*TES*
Solar power tower	*SPT*
Supercritical carbon dioxide	sCO_2
Calcium looping	*CaL*
Thermochemical energy storage	*TCES*
Direct normal irradiance	*DNI*
Levelized cost of energy	*LCOE*
Levelized cost of storage	*LCOS*
Solar multiple	*SM*
Storage capacity	*STO*
Key performance indicator	*KPI*
Compressor	*Comp*
Molten Salt	*MS*
Turbine	*Turb*
Thermal oil	*TO*
Receiver	*rcv*
Carbonator	*carb*
PB	*Power block*
BOP	*Balance of plant*
Cost	*C*