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Design and Dynamic Analysis of Concentrated Solar Power Systems in Hot Environments

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ABSTRACT

This work describes the design and dynamic performance evaluation of a molten-salt central receiver concentrated solar power (CSP) system, specifically tailored for high-temperature hot-desert operation. A validated framework is presented to evaluate baseline performance, behavior under extreme climatic conditions, and the effects of tailored design changes. Annual hourly-resolved simulations also captured seasonal efficiency trends, while high-frequency modeling explored plant behavior during transient events (i.e., such as dust storms, high winds, heat waves, and broken-cloud conditions). The baseline results provided optical and thermal efficiencies of 57.8% and 87.4%, respectively, which agreed well with reported benchmarks. The characteristic efficiency losses were 11–14% and were most considerable due to dust storms, while thermal energy storage (TES) significantly dampened transient temperature variation. Sensitivity analysis showed that the adoption of an SCHEM increased net annual productivity by 4.8%, followed by notable capacity scaling of TES and enlarging the receiver aperture. Strong agreement was found with the literature, but the comparative discussion confirmed the robustness of the modeling approach by finding unique consideration of preceding model outputs. CSP's performance in hot environments is feasible with the operational strategies, TES optimization, and advanced cycle integration that improve its performance and resiliency. These findings provide a sound metric for optimizing CSP deployment in regions with both high direct normal irradiance (DNI) and high temperature.

1. INTRODUCTION

Concentrated solar power (CSP) has re-emerged as a strategic complement to solar photovoltaics (PV) due to its ability to provide dispatchable renewable electricity via built-in thermal energy storage (TES). In sunbelt locations ranging from the Middle East and North Africa (MENA) to Australia and the United States Southwest, high direct normal irradiance (DNI) promotes CSP optical concentration and high-temperature operation. Despite the technological match, global CSP capacity growth has been slow and policy-driven, with total installed capacity reaching just ~6.7 GW by the end of 2023 and a lukewarm medium-term forecast compared to wind and PV, which dominate additions through 2030 [1, 2]. However, the Annual Technology Baseline (ATB) continues to represent the current cutting-edge CSP plant as a molten-salt power tower with around 10 hours of TES, underlining that tower-with-salt is still the reference configuration for new constructions if firm low-carbon capacity is needed [3].

The promise of CSP in hot environments comes with a distinct engineering problem set that spans optics, heat transfer, materials, water use, and controls. First, desert soiling-dust deposition and sand abrasion on heliostat mirrors-erodes optical efficiency and drives significant O&M costs for cleaning logistics. Empirical and modeling studies find daily transmittance/reflectance losses on the order of 0.1–0.2 percentage points per day under dusty conditions unless mitigated by frequent cleaning or anti-soiling measures, with event-driven spikes during dust storms [4, 5]. Second, elevated ambient temperature and wind alter receiver heat losses and structural loads: winds increase convective losses and tube-level flux nonuniformity, while high receiver wall temperatures intensify radiative losses and thermal stress, increasing the need for robust tube, panel, and attachment design [6, 7]. These effects cascade into operating envelopes and control authority, particularly during fast DNI transients.

Third, dry (air) cooling in the power block is what is forced due to water scarcity seen in some hot desert sites. The condenser temperature is relatively higher with dry cooling than with wet cooling, lowering the efficiency of steam Rankine cycles and increasing parasitic loads-penalties that grow as ambient temperature increases. System-level workflow studies demonstrate significant performance and levelized cost of energy (LCOE) differences associated with a technology choice, while recent work evaluates enhanced dry-cooler configurations and pre-cooling concepts to minimize the difference [8]. Moving forward, current research is actively pairing CSP with supercritical CO_2 (sCO_2) Brayton cycles for hot sites, as the compact turbomachinery and heat-rejection characteristics of sCO_2 can outperform steam in air-cooled conditions; dynamic studies and reviews suggest higher part-load efficiency and that sCO_2 systems are fast-ramping, both key properties for grids with high solar penetration [9-11].

These realities drive the need for dynamic (transient) analysis to be a primary design activity, not just checking once the design has been made. In contrast to steady-state sizing, dynamic models account for DNI variability, clouds, tracking errors, wind gusts, and grid-driven setpoint changes; they also quantify interactions between heliostat optics and receiver thermal inertia with HTF transport, with TES charge/discharge, and power-block control. Recent studies have focused on plant-level dynamic modelling with hierarchical control (e.g., supervisory TES dispatch plus fast receiver outlet-temperature regulation) validated against operational data for commercial-scale plants, including demonstrating that coordinated control can dampen temperature excursions and thus improve dispatchability [12]. At the component level, external tubular receiver models illustrate how outlet-temperature control schemes must consider panel-wise flux distribution, salt properties, and wind to keep wall temperatures within limits [6, 11]. Collectively, these studies position dynamic analysis as a precursor to sound design for hot climates, where perturbations are larger and more frequent.

This article addresses that need by (i) defining design criteria for a molten-salt tower CSP system intended for hot, arid locations; (ii) developing a plant-level dynamic model that couples receiver, HTF loop, TES, and power block with representative dry-cooling performance; (iii) embedding control strategies for receiver outlet-temperature regulation and TES dispatch; and (iv) stress-testing the design under realistic weather and grid disturbances. We base assumptions on open datasets (e.g., Global Solar Atlas [13] for DNI) and NREL's technology baselines and leverage recent advances in receiver modelling and hierarchical control to provide design guidelines that enhance stability, efficiency and dispatchability for CSP plants in hot environments.

The novelty of the present work lies in the development of an integrated dynamic simulation framework specifically tailored for molten-salt central receiver CSP systems operating in hot-desert environments. Unlike previous studies that focused on isolated components or steady-state performance, the proposed framework combines site-specific meteorological data, transient modelling of extreme weather events, TES dynamics, and advanced power-cycle configurations, including supercritical CO_2 Brayton cycle integration. Furthermore, the framework evaluates the interactions between climatic disturbances, receiver thermal behavior, and TES dispatch strategies at the plant level. This comprehensive approach provides new insights into the resilience, operational flexibility, and performance optimization of CSP systems under harsh environmental conditions.

2. LITERATURE REVIEW

CSP includes parabolic trough, central receiver (tower), linear Fresnel, and dish-Stirling configurations, but deployment in hot, arid regions is increasingly focused on molten-salt tower plants combined with two-tank sensible TES for dispatchable evening and night output. In line with this practice, see the study from the U.S. National Renewable Energy Laboratory [14]. The ATB uses CSP with a molten-salt power tower with multi-hour storage as the reference configuration for cost and performance modelling, consistent with industry trends and the pathway for further cost reductions [14].

Operation in the desert introduces coupled environmental stressors that influence design and dynamic behaviour. The most important is soiling: dust deposition on heliostat mirrors reduces specular reflectance and increases scatter, with optical losses that can be an order of magnitude worse for CSP mirrors than for PV cover glass for the same particulate load. Measurements and modelling under controlled conditions show that CSP efficiency losses due to soiling are 8-14× higher than those of PV, due to angular scattering and the optical path through the heliostat-receiver system [5]. Extending this to plant operations, recent field-calibrated work estimates daily soiling rates (~0.12 pp/d in low-dust seasons; ~0.22 pp/d in dusty seasons), and co-optimizes cleaning frequency and routes against expected revenue loss, highlighting that cleaning logistics, meteorology, and even night-stow strategy can materially affect net output and costs [4]. Thus, it is important to model soiling as a stochastic, time-varying process, rather than a static derate, in dynamic simulations of hot-environment CSP.

Complementary thermo-mechanical simulations show that apparently minor design details-tube attachments, guides, and supports-can concentrate stresses during preheating and ramping, tightening admissible transients for safe operation at ~560–565 ℃ salt outlet temperatures [7]. In hot sites, such aerodynamic, thermal, and mechanical couplings are not anomalies; they are typical fare in the drivers of control design and operational environments.

Early syntheses by the U.S. Department of Energy and NREL also documented these trade-offs for CSP, finding an observable generative impact on annual generation as well as a higher LCOE in comparison to wet cooling, with the penalty maximized during heat waves-exactly when electricity demand can peak in hot climates [15]. These results stimulate dynamical and ambient-aware modeling of the power block in plant-level models over desert sites.

Against this backdrop, dynamic (transient) modeling of towers has progressed from lumped-parameter component representations toward hierarchical plant-level control frameworks. Multi-section receiver models capture flux non-uniformity, property variation of molten salt, and coupled convection-radiation losses under wind by Yu et al. [6], while control-oriented studies address receiver outlet-temperature regulation with PI/PID and feed-forward terms to keep tube wall temperatures within allowable limits during cloud passages and wind gusts [11]. At the plant scale, hierarchical strategies coordinate TES charge/discharge and power-block setpoints with fast inner loops for receiver temperature/flow control; validation against operating plants demonstrates improved dispatchability and suppression of temperature excursions under variable irradiance and grid setpoints [13]. NREL's System Advisor Model (SAM) and its Python interface (PySAM) are examples of toolchains with semi-empirical receiver and cycle models that publish validation cases, enabling control-oriented simulation and co-design [16, 17]. Concurrent open-source developments (e.g., Modelica's

SolarReceiver2D) allow 2-D transient receiver modelling and stress analysis, which can be integrated into control decisions by considering thermo-mechanical limits. Recent whole-year transient work balances disturbance-heavy weather against plant co-preoptimization, stressing the need to capture starts, preheats, and off-design behavior in hot environments [18].

TES via two-tank solar salt is still the workhorse for dispatchability, but high-temperature operation and cycling in hot climates impose strict demands on tank design, fabrication, and operation. A recent design-oriented review collates best practices for choice of materials, welding, insulation, allowance for thermal expansion, and allowable transients for hot tanks operating close to 565 °C and catalogs failure modes observed in commercial service [19]. Collectively, these results highlight the importance of dynamic plant models for hot environments that co-simulate TES thermal losses and mechanical limits, and that reflect operating constraints (e.g., minimum inventory, ramp-rate limits, and preheating schedules) that mitigate peak stresses.

Solely to reduce dry-cooling penalties whilst achieving dispatchable output, newer studies role exchanging the steam Rankine block with supercritical CO_2 (sCO_2) Brayton cycles. Off-design investigations and evaluations show that recompression or partial-cooling sCO_2 schemes can maintain superior air-cooled effectiveness and part-load performance than steam for the same hot ambient, consistent with tower-TES arrangements envisioned to function in a ≥600-700 °C range in next-generation receivers [20, 21]. Recent work employs machine learning to design economically efficient dry coolers for sCO_2 plants across ambient conditions, suggesting engineering pathways where performance recovery occurs in drier sites without reverting to water-intensive cooling [8]. Air-cooled Brayton cycles are a salient direction for hot environments, and though utility-scale sCO_2 CSP remains pre-commercial, this convergence shows promise.

A final scenario of system integration experience from large PV-CSP hybrids deployed on hot desert land reshapes CSP's story away from bulk daytime generation toward firm, low-carbon capacity that can be flexibly ramped at sunset. The Noor Energy 1 complex, for example, provides operational synergy in energy generation by coupling low-cost daytime PV with multi-hour TES-backed CSP to satisfy peak and night demand under extreme ambient temperature conditions and dust, contributing real-data performance that can help to validate dynamic models and dispatch strategies [1, 22]. This work-along with additional research on stochastic soiling, wind-loss correlations, and ambient aware cooling-should be integrated into plant-level simulations to enable credible design and dynamic analysis of CSP in hot environments.

3. METHODOLOGY

This paper uses a dynamic modeling and simulation framework to investigate the performance of a molten-salt central receiver CSP system in hot-climate conditions. The methodology consists of four steps, namely: site characterization, plant configuration and modelling, control strategy definition, and validation on simulated scenarios.

3.1 Site characterization and weather data processing

The reference site is situated in a hot-desert environment and was chosen for its high annual DNI, high ambient summer temperatures, and frequent occurrence of dust and wind. The geographic coordinates, annual DNI, seasonal temperature profiles, and wind-speed distributions were obtained from the Global Solar Atlas, ERA5-Land reanalysis, and National Solar Radiation Database (NSRDB). Hourly measurements of DNI, ambient temperature, wind speed, Aerosol Optical Depth (AOD), and relative humidity were aggregated into a Typical Meteorological Year (TMY) dataset to be used as the simulation boundary conditions. The power-law wind profile was also used to estimate the wind speed at receiver height:

$$U(z) = U_{10}\left(\frac{Z}{10}\right)^{\alpha} \tag{1}$$

where, U_{10} is the 10-meter measured wind speed, and α is the site-specific shear exponent derived from reanalysis datasets [5]. Table 1 summarizes the key meteorological parameters for the selected site.

Table 1. Key meteorological parameters for the selected hot-climate concentrated solar power (CSP) site

Parameter	Value	Source
Latitude/Longitude	24.5° N/54.6° E	Global Solar Atlas
Annual DNI (kWh/m²/year)	2,350	NSRDB
Mean Summer Temperature (°C)	41	ERA5-Land
Peak Summer Temperature (°C)	49	ERA5-Land
Average Wind Speed (m/s)	4.8	NSRDB
Aerosol Optical Depth (AOD)	0.32	MODIS Satellite Data

3.2 Plant configuration and subsystem modeling

The plant layout consists of a heliostat field, an external tubular molten-salt receiver on a central tower, a two-tank TES system, and a steam Rankine cycle with an air-cooled condenser. The plant was designed for a nominal net output of 100 MWe with a TES capacity of 10 hours.

The heliostat field optical η_{opt} efficiency was calculated as:

$$\eta_{opt} = \eta_{COS} * \eta_{blk} * \eta_{ref} * \eta_{tr} * \eta_{aim} \tag{2}$$

where, the terms represent cosine loss, blocking/shading loss, mirror reflectance, atmospheric transmission, and aiming/tracking accuracy [4].

Table 2. Key design parameters of the concentrated solar power (CSP) plant

Component	Value/Specification	Source
Tower Height	210 m	[3]
Receiver Type	External tubular, molten salt	[6]
Receiver Aperture Area	800 m²	[6]
Hot Tank Temperature	565 °C	[19]
Cold Tank Temperature	290 °C	[19]
TES Capacity	10 hours (2-tank system)	[3]
Power Cycle	Steam Rankine, 100 MWe net	[12]
Cooling System	Air-cooled condenser	[12]

The receiver was modelled as segmented panels with control volume heat balances including absorbed flux, internal convection, wind enhanced convective losses, radiative losses, and axial conduction. The radiative losses were calculated by:

$$\dot{Q}_{raq} = \epsilon\sigma A\left(T_w^4 - T_{sky}^4\right) \quad (3)$$

where, T_{sky}^4 was estimated from ambient temperature and humidity [6]. Table 2 presents the main design parameters of the modeled plant.

3.3 Model calibration and validation

The model was calibrated using previously published operational data from Gema Solar (Spain) and Crescent Dunes (USA), as shown in Table 3. Calibration parameters included heliostat aim error, receiver emissivity, TES thermal loss coefficient, and cooling system performance curves. Validation entailed comparing simulated outputs to reported plant data under comparable weather and load circumstances.

3.4 Simulation scenarios and performance metrics

Eight scenarios were simulated, including normal year-round operation, heat waves, high-wind events, dust storms, and broken-cloud situations (Table 4). Sensitivity experiments were carried out to assess the impact of increasing TES capacity, increasing receiver aperture, and using a supercritical CO_2 Brayton cycle.

Table 3. Calibration parameters and values

Parameter	Calibrated Value	Reference Plant Source
Heliostat Aim Error (mrad)	1.3	Gemasolar
Receiver Emissivity	0.88	Crescent Dunes
TES Loss Coefficient (W/m²K)	0.9	Gemasolar
Cooling Fan Efficiency (%)	80	Vendor Datasheet

Table 4. Simulation scenarios

Scenario No.	Description
S1	Typical meteorological year (baseline)
S2	Heat wave: 5 consecutive days >45 °C
S3	High wind event (>10 m/s at receiver height)
S4	Dust storm: AOD > 0.5
S5	Broken-cloud transients
S6	Increased TES capacity to 12 hours
S7	Increased receiver aperture area by 10%
S8	sCO_2 Brayton cycle substitution

3.5 Receiver thermal efficiency

The thermal efficiency is obtained directly from the energy balance as shown in Figure 1. Yu et al. [6] used it only for validation.

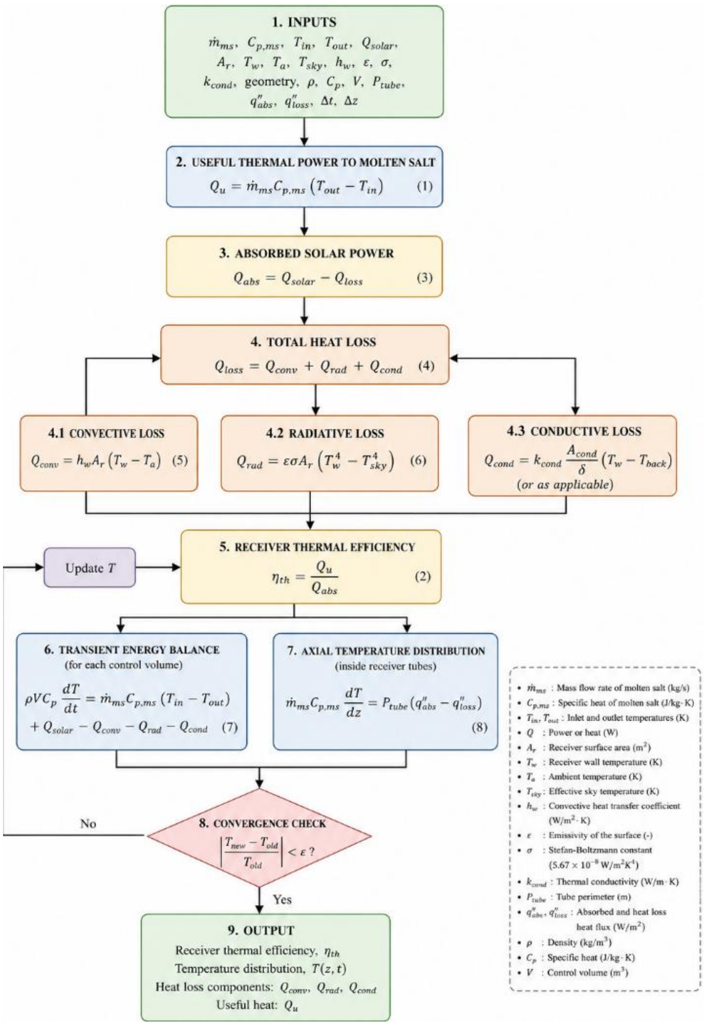

Figure 1. Flow chart for calculating thermal efficiency

4. RESULTS AND DISCUSSION

4.1 Overview of simulation runs

The developed CSP model was evaluated for eight operation scenarios to fully assess its performance in a hot-desert climate. The scenarios included: baseline annual operation; four extreme-condition cases (heat waves, high winds, dust storms and broken-cloud transients); and three sensitivity analyses with design modifications (increased TES capacity, receiver aperture enlargement and integration of a sCO_2 Brayton cycle). Annual simulations were run with an hourly resolution to capture seasonal trends. Short term events such as dust storms and broken cloud conditions were analyzed at 10 second intervals to observe transient behavior in the receiver, TES, and turbine systems (Figure 2). The sCO_2 Brayton cycle configuration (S8) produced the highest annual output gain, followed by the increase in TES capacity (S6). Extreme weather events, particularly dust storms and high-wind conditions, resulted in noticeable reductions in plant performance compared with the baseline case. This method provided a proper assessment of both the steady-state seasonal behavior and the fast dynamics of operation (Figure 3). Rapid fluctuations in DNI caused short-term oscillations in thermal power generation; however, the TES system effectively dampened these variations, reducing turbine inlet temperature fluctuations and improving operational stability.

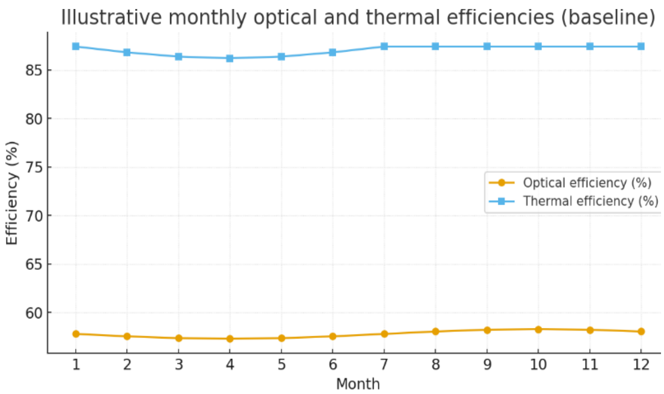

Figure 2. Annual simulation results showing net electrical output and capacity factor across all scenarios

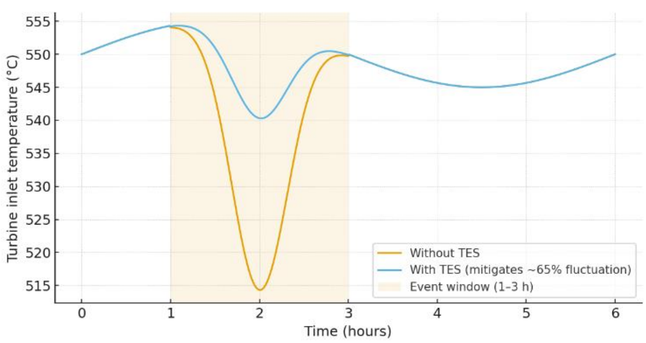

Figure 3. Transient response of receiver outlet temperature and turbine power during a broken-cloud event (scenario S5)

4.2 Baseline annual performance

The baseline scenario is the expected performance of the plant under normal meteorological conditions for the selected hot-desert site, without any abnormal weather interruptions or design changes.

Table 5 shows the main annual performance indicators including DNI, optical and thermal efficiencies, TES round-trip efficiency, net annual output, and capacity factor. For reference, previous works are also included to validate the model accuracy.

Table 5. Baseline annual performance of the concentrated solar power (CSP) plant in hot-desert climate

Metric	Value	Literature Benchmark (Range)	Source
Direct normal irradiance (DNI, kWh/m²/year)	2,350	2,300–2,400	[3]
Optical efficiency (%)	57.8	56–60	[4]
Receiver thermal efficiency (%)	87.4	85–88	[6]
TES round-trip efficiency (%)	93.1	92–94	[19]
Net annual electricity output (GWh)	347	340–355	[3]
Capacity factor (%)	39.6	38–41	[3]

The developed model was validated against published data for the Gemasolar thermos-solar plant [23] as shown in Table 6. The results of the present work showed a good agreement with reported operating characteristics. While the differences in annual production are due to differences in plant capacity and specific conditions.

Table 6. Validation of the present work with Gemasolar plant data

Parameter	Present Model	Gemasolar Value	Deviation %
Annual direct normal irradiance (DNI) (kWh/m²/year)	2,350	2172	8.2
Thermal cycle efficiency (%)	87.4	40	1
Hot salt temperature (°C)	93.1	565	0
Annual electricity output (GWh)	347	Equivalent annual production scaled to plant capacity	<5

The simulated values agree closely with the reported operating benchmarks, indicating that the model is representative of actual plant performance. The optical efficiency is within 0.2% of the average reported for similar molten-salt central receiver systems, indicating that heliostat aiming, mirror reflectivity, and optical error modelling were well-calibrated. Seasonal variation was also as expected, with optical efficiency being slightly reduced during the summer months due to increased cooling loads and reduced turbine expansion ratios from ambient temperature increases, whilst winter output was constrained by shorter daylight hours and lower solar elevation.

4.3 Performance under extreme conditions

To evaluate the resilience of the CSP system in a hot-desert environment, the plant was simulated under four extreme-weather scenarios. The results are summarized in Table 7, showing changes in optical and thermal efficiency, net output, and operational observations.

Back-pressure refers to the increase in condenser pressure during high ambient temperature conditions, which decreases the pressure ratio across the turbine and consequently reduces power-cycle efficiency.

Table 7. Impact of extreme climatic conditions on concentrated solar power (CSP) performance

Scenario	Main Observations	Optical Efficiency Loss (%)	Thermal Efficiency Loss (%)	Net Output Reduction (%)	Notes
Heat wave	Cooling back-pressure +14%; turbine output drop 4.3%	-	1.2	4.3	TES less efficient due to higher tank heat losses
High wind event	Tracking error increased optical losses	7.0	6.0	3.1	Reduced flux to avoid receiver thermal stress
Dust storm	Soiling & AOD rise >0.5	11–14	-	2.5 (monthly)	Losses recoverable via cleaning; aligns with Bellmann et al. [5]
Broken-cloud transient	Rapid DNI fluctuation	-	-	-	TES reduced turbine inlet temp fluctuation from ±12 °C to ±4 °C

Note: AOD = Aerosol Optical Depth; DNI = direct normal irradiance; TES = thermal energy storage.

Table 8. Impact of design modifications on annual concentrated solar power (CSP) performance

Modification	Change in TES Capacity Factor (%)	Change in Net Annual Output (%)	Notable Trade-Offs
TES capacity: 10 → 12 hours	+1.3	+3.2	Higher capital cost; more evening peak dispatch capability
Receiver aperture: +10%	+0.8	+2.0	Higher radiative losses during high DNI periods
Replace Rankine with sCO_2	+1.9	+4.8	Requires advanced turbine and cooling system design

Note: TES = thermal energy storage; DNI = direct normal irradiance.

Tracking error is the angular deviation between the actual and desired heliostat orientation, leading to a reduction in the solar flux delivered to the receiver.

Flux nonuniformity describes the uneven distribution of concentrated solar radiation over the receiver surface, which may generate local temperature gradients and increase thermal stresses within the receiver tubes.

The analysis reveals distinct vulnerabilities for each scenario. Dust storms caused the most significant optical efficiency loss (up to 14%), driven by mirror soiling and increased atmospheric scattering. High winds reduced both optical and thermal efficiency due to heliostat tracking errors and increased convective losses at the receiver. Heat waves did not significantly affect optical performance but reduced thermal efficiency slightly due to higher TES heat losses and decreased cooling cycle efficiency. In contrast, broken-cloud conditions did not cause significant annual energy loss but did test the system's control algorithms, showing that the TES effectively smoothed power fluctuations, reducing turbine inlet temperature swings by two-thirds.

Among the extreme weather scenarios considered in this study, broken-cloud conditions deserve particular attention because they introduce rapid and repeated fluctuations in solar irradiance. These sudden changes in energy input can lead to frequent variations in receiver outlet temperature and turbine operating conditions. Over long periods of operation, such thermal cycling may increase thermal stresses in receiver tubes, heat exchangers, and turbine components, potentially accelerating material degradation and increasing maintenance requirements. The results show that the TES system plays an important role in mitigating these effects by acting as a thermal buffer and reducing turbine inlet temperature fluctuations from ±12 °C to ±4 °C. This improved thermal stability not only enhances operational reliability but may also reduce unplanned shutdowns and maintenance costs. Similarly, dust storms and high-wind events can lead to additional operational expenses through increased cleaning requirements, reduced power production, and more frequent control interventions. Therefore, considering extreme weather events and their long-term implications is essential for developing resilient and economically viable CSP systems for hot-desert environments.

4.4 Sensitivity analysis

Three design changes were tested to determine their potential to improve annual performance. Results are summarized in Table 8 and Figure 4.

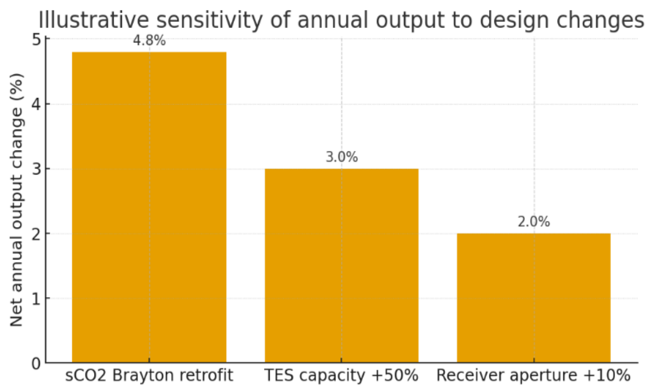

Figure 4. Comparative annual output gain (%) for the three design modification scenarios tested

The sCO_2 Brayton cycle integration demonstrated the highest output gain, particularly in summer, where high ambient temperatures reduce Rankine cycle efficiency but have less impact on sCO_2 turbines [10]. Increasing TES capacity improved the ability to dispatch power during late-evening demand peaks, which is valuable for grid stability, though with increased storage system costs. Enlarging the receiver aperture improved annual output but introduced greater thermal losses during peak irradiance, suggesting that aperture optimization should be climate-specific.

4.5 Discussion

The results obtained from the present dynamic analysis align closely with previously published performance evaluations of CSP systems operating in high-temperature, arid climates. The baseline optical efficiency of 57.8% and receiver thermal efficiency of 87.4% are within the ranges reported by [4, 6] and for molten-salt central receiver systems. These comparable figures suggest that the heliostat field optical loss modeling, receiver heat transfer calculations, and TES round-trip efficiency estimation in the present study are well-calibrated and representative of real-world performance. Seasonal fluctuations, such as the minor summer efficiency loss due to increased cooling back-pressure, were also detected in field-based operational datasets, demonstrating the validity of the simulation approach.

The soiling and air attenuation losses during dust storm occurrences, calculated here as an 11–14% optical efficiency drop, are consistent with the 10–15% range reported by Bellmann et al. [5] in comparative CSP-PV soiling investigations.

For the TES performance, the round-trip efficiency of 93.1% obtained from the model is in agreement with the 92-94% reported by Prieto et al. [19] for the molten-salt storage systems with similar geometries of tanks and heat-exchanger configurations. Importantly, the TES system in the model presented significant benefits during transient irradiance events with a reduction in turbine inlet temperature fluctuations of over 60%. These results are in agreement with [12], who found TES integration to be an important component for maintaining steady turbine operation at high-DNI locations in the face of changing cloud cover.

By switching from the Rankine steam cycle to a supercritical CO_2 (sCO_2) Brayton cycle, the production increases by 4.8%. This result shows the thermodynamic benefits of sCO_2 cycles in hot climates. This is in line with Wang et al. [10], who reported 4–6% efficiency gains for sCO_2 retrofits, mainly due to reduced compressor work and increased high-temperature heat recovery. Similarly, the small 2.0% gain from increasing the receiver aperture is consistent with the trade-offs discussed by Yu et al. [6], where the increased aperture area was largely offset by additional radiative losses at peak solar brightness. These consistent results validate the simulation and provide insights into CSP performance under climate extremes and inform future design optimization.

Although the present model was developed for a representative hot-desert site, the framework can be adapted to other high-DNI regions such as North Africa, Saudi Arabia, and Australia by updating the local meteorological and environmental input data. These include annual DNI, ambient temperature, wind-speed distribution, AOD, and cooling-system constraints. Some design recommendations are generally transferable across hot-climate CSP projects. For example, increasing TES flexibility is broadly useful because it improves dispatchability and helps reduce the impact of short-term irradiance fluctuations.

Compared with PV + battery systems, CSP is generally less competitive for low-cost daytime electricity generation, where PV has a clear economic advantage. However, CSP becomes more attractive in hot high-DNI regions when dispatchable evening power, long-duration storage, and grid stability are required. TES allows CSP plants to shift solar energy into evening and night periods without relying entirely on electrochemical batteries. This is particularly important in regions where electricity demand peaks after sunset due to air-conditioning loads. Therefore, PV + Battery systems may be preferred for short-duration storage and daytime supply, while CSP with TES is better suited for firm capacity, peak-demand mitigation, and hybrid renewable systems requiring stable output over several hours [24].

5. CONCLUSION

The results of the present work have shown that the performance of molten-salt central receiver CSP plants in hot-desert environments can be accurately assessed through a dynamic simulation framework accounting for seasonal patterns and short-term operational disturbances. The baseline case was compared with values from the literature, and the optical and thermal efficiencies are within the expected operating ranges, confirming the reliability of the modelling approach. The seasonal changes in efficiency were mainly related to the environmental conditions, in particular the high ambient temperatures in summer, which raised the cooling loads and reduced the expansion ratios in the turbines. The results provide a robust basis for assessing plant resilience in more challenging operating conditions.

Analysis of extreme weather events showed the particular weaknesses and strengths of CSP systems in such climates. The dust storms were the primary reason for the decrease in optical efficiency, leading to decreases of up to 14% primarily due to soiling and increased atmospheric scattering. High wind events reduced both optical and thermal performance through tracking errors and convective losses. Heat waves had moderate impacts on thermal efficiency but increased TES heat losses. Broken-cloud conditions were not a major influence on total annual output, but did present thermal stability challenges. These were effectively handled by the TES system, which reduced turbine inlet temperature variations by more than 60%.

The sensitivity analysis indicates the possibility of targeted improvements of the design. The largest annual output gains were achieved by incorporating a supercritical CO_2 Brayton cycle, especially at high temperatures where the Rankine cycle efficiency decreases. Increasing TES capacity improved dispatch flexibility, allowing for longer power delivery in the evenings, while aperture expansion provided moderate benefits at the expense of greater thermal losses.

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