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Economic and environmental assessment of a concentrated solar power system using sand as a heat transfer medium

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Abstract

Concentrated solar power (CSP) systems offer a promising pathway to reduce fossil fuel dependence, particularly in regions with abundant sunlight. This study evaluates the economic, environmental, and fuel-saving benefits of a CSP system using locally sourced sand as a heat transfer medium. The system integrates a sand–air heat exchanger, a microturbine (100 kWe), and a 300 kW thermal battery. Tested during peak solar hours, the turbine achieved 39.5% thermal efficiency using heliostats to concentrate solar energy and heat sand particles, transferring thermal energy to drive the turbine. Operational data show a 20% reduction in fuel consumption and carbon dioxide emissions, resulting in significant financial reductions and environmental benefits. The thermal battery enables continued operation during cloudy periods or nighttime by storing excess heat, further enhancing fuel efficiency and emission reductions. Reaching technology readiness level 7 in 2018, the prototype demonstrates viability for regions with high direct normal irradiation, such as Saudi Arabia. Key performance factors include heliostat quality, heat exchanger efficiency, and sand thermal properties. Despite challenges like heliostat degradation since 2009, the system shows scalability potential. Solar contribution could reach 80% with an optimized design, amplifying economic and environmental gains. The study highlights the promise of sand-based CSP systems in reducing fossil fuel reliance and supporting global sustainability goals. Future improvements should focus on enhancing heliostat reflectivity, refining heat exchanger design, and selecting sand with better thermal stability. These advancements could pave the way for cost-effective, renewable energy solutions in desert regions rich in solar and sand resources.

Keywords: Concentrated solar power; Sand-based heat transfer; Fuel consumption reduction; Carbon dioxide emissions; Thermal battery storage; Heliostat efficiency; Renewable energy

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent need to address climate change, reduce greenhouse gas emissions, and transition away from fossil fuels. Renewable energy technologies are at the forefront of this shift, with solar power playing a pivotal role due to its abundance and potential for scalability. Among solar technologies, concentrated solar power (CSP) stands out for its ability to harness solar energy efficiently and provide dispatchable power through thermal energy storage. This study investigates the cost-saving potential of a sand-based CSP system, emphasizing its ability to reduce fuel consumption and operational costs. By leveraging locally available sand as a heat transfer medium, CSP systems provide a key benefit over photovoltaic (PV) systems. CSP systems are more affordable and have efficient thermal energy storage capabilities. In addition, sand-based CSP can heat falling particles to 720°C or more, surpassing the limitations of steam and molten-salt CSP, which typically do not exceed 560°C.

Unlike PV systems, which convert sunlight directly into electricity, CSP systems use mirrors or lenses to concentrate solar radiation, generating high-temperature heat to drive power cycles, typically through steam or gas turbines. This study evaluates a novel CSP system that employs locally sourced sand as a heat transfer medium, integrated with a sand–air heat exchanger, a Turbec T100 microturbine generating 100 kWe, and a thermal battery storage system with a capacity of 300 kW thermal, as shown in Figures 1 and 2. This system achieved a turbine thermal efficiency of 39.5% with solar contribution.

1.1. Background on CSP

CSP systems are particularly advantageous in regions with high direct normal irradiation (DNI), such as the Middle East and North Africa (MENA) region, where Saudi Arabia is a key player.[1] These regions receive intense sunlight, making them ideal for CSP deployment. The ability to store thermal energy allows CSP systems to generate electricity during non-sunny periods, such as at night or during cloudy weather, addressing one of the primary limitations of solar energy: intermittency. Traditional CSP systems use molten salts or synthetic oils as heat transfer fluids.[2] However, these materials are costly, pose environmental risks, and face operational challenges, such as corrosion and limited temperature ranges. Molten salts, for instance, solidify at lower temperatures, requiring energy-intensive heating systems to maintain fluidity, while synthetic oils degrade at high temperatures, limiting their efficiency.

In contrast, sand, an abundant and low-cost material, offers significant advantages as a heat transfer medium. Sand exhibits thermal stability at high temperatures, making it suitable for CSP applications. Its availability in desert environments, particularly in regions like Saudi Arabia, reduces dependency on imported materials and lowers system costs. Previous studies have explored the use of sand in CSP systems,[3] highlighting its potential to improve system scalability while minimizing operational costs. This research builds on these findings by developing and testing a prototype CSP system that integrates solar heliostats, a particle heating receiver (PHR), a sand–air heat exchanger, and a thermal energy storage unit.

1.2. System design and components

The prototype CSP system evaluated in this study incorporates several innovative components designed to maximize efficiency and leverage local resources. The system uses solar heliostats to concentrate sunlight onto a PHR, where sand is heated to high temperatures. The heated sand transfers the thermal energy to a sand–air heat exchanger, which drives the Turbec T100 microturbine to generate 100 kWe of electricity. A thermal battery storage

Figure 1. The concentrated solar power system in the King Saud University's campus from different views

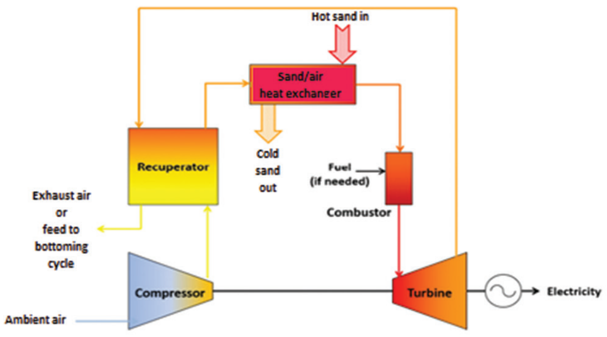

Figure 2. The layout of concentrated solar power components

system with a capacity of 300 kW thermal allows the system to store excess heat for later use, ensuring continuous power generation. The turbine thermal efficiency of 39.5% is achieved through optimized heat transfer and energy conversion processes.

The use of sand as a heat transfer medium is a key innovation of this system. Sand is abundant in Saudi Arabia, aligning with the country's Vision 2030, which emphasizes sustainable energy development and economic diversification.[4] Utilizing locally sourced materials reduces reliance on imported molten salts or synthetic oils, lowering both capital and operational costs. The sand–air heat exchanger is another critical component, enabling efficient heat transfer from the sand to the working fluid that drives the microturbine. The thermal battery storage system enhances the system's flexibility, allowing it to provide electricity during periods of low solar irradiation, such as nighttime or cloudy conditions.

1.3. Testing and performance in real-world conditions

The prototype CSP system was tested in Riyadh,[5] Saudi Arabia, under real-world conditions. Testing was conducted during peak solar hours (9 AM–3 PM) in July, when DNI levels are at their highest. The operational data collected provided valuable insights into the system's performance, including economic savings, fuel consumption reduction, and environmental impact. The system achieved a 20% reduction in fuel consumption during on-sun operations, resulting in proportional decreases in carbon dioxide (CO_2) emissions. This reduction is significant, as it demonstrates the potential of sand-based CSP systems to contribute to global efforts in mitigating climate change.

The thermal battery storage system proved to be a critical component, enabling the system to maintain power generation during non-sunny periods. This capability addresses one of the primary challenges of solar energy—its dependence on sunlight availability. The system can provide electricity on demand by storing thermal energy, improving its reliability, and making it a viable alternative to conventional power generation.

1.4. Economic and environmental benefits

This study was motivated by the need to address the high costs and environmental footprint of conventional power generation. By integrating sand as a heat transfer medium, the system achieves significant cost reductions compared to traditional CSP systems. Sand is abundant, inexpensive, and thermally stable, reducing the need for costly maintenance associated with molten salts or synthetic oils. The system's reliance on local resources further enhances its economic viability, particularly in desert regions where sand is readily available.

The environmental benefits of the system are equally compelling. The 20% reduction in fuel consumption during on-sun operations translates to a proportional decrease in CO_2 emissions, contributing to global efforts to combat climate change. By scaling the system to achieve an 80% solar contribution, the potential for emission reductions increases significantly. This target percentage was set based on several factors, including planned improvements to heat exchanger design in Phase 2 of the project. The system will be implemented in Turaif in northern Saudi Arabia, where the DNI is higher than in Riyadh. In addition, advanced and newly developed solar reflectors will be designed and manufactured, replacing the outdated ones used in Phase 1. The system will also be scaled up to a larger capacity of 1.2 MWe, with thermal energy storage batteries of higher capacity. Thus, the potential for emission reductions increases significantly. This aligns with Saudi Arabia's Vision 2030, which seeks to diversify the economy and reduce reliance on fossil fuels through investments in renewable energy.

1.5. Potential for large-scale implementation

The success of the prototype CSP system in Riyadh suggests significant potential for large-scale implementation, particularly in sun-rich regions like the MENA region. The system's reliance on locally sourced sand makes it particularly well-suited for desert environments, where traditional CSP systems face challenges related to the cost and availability of heat transfer fluids. The developed technology has achieved technology readiness level 7, indicating a successful prototype demonstration in an operational environment, as defined by NASA.[6] By leveraging abundant local resources, the system can be scaled to meet the energy demands of larger populations, contributing to the global transition to renewable energy.

However, large-scale implementation will require addressing several challenges, including equipment durability and system optimization. The degradation of heliostats over time underscores the need for durable materials that can withstand prolonged exposure to harsh environmental conditions. Similarly, the sand–air heat exchanger and thermal battery storage system must be designed to operate reliably on a scale. Advances in materials science and engineering could help overcome these challenges, enabling the widespread adoption of sand-based CSP systems.

1.6. Alignment with Saudi Arabia's Vision 2030

The development of this innovative sand-based CSP system aligns closely with Saudi Arabia's Vision 2030, which prioritizes sustainable energy development, environmental protection, and economic diversification. By reducing reliance on fossil fuels and leveraging abundant local resources such as desert sand and solar irradiance, the system supports the country's strategic goal of increasing renewable energy capacity and enhancing energy security. The economic benefits of the system, including reduced fuel consumption, lower operational costs, and long-term savings, also contribute to the diversification of Saudi Arabia's economy, reducing dependence on oil revenues and fostering new industrial opportunities.

Furthermore, the system's environmental benefits support Saudi Arabia's commitment to reducing greenhouse gas emissions and combating climate change. By integrating advanced renewable energy technologies like CSP into the national energy mix, Saudi Arabia can position itself as a regional and global leader in the transition to clean energy. The successful testing of the prototype in Riyadh demonstrates the feasibility and scalability of this approach, providing a replicable model for other sun-rich regions to follow and adapt. This aligns with broader national efforts to localize renewable energy technologies, attract foreign investment, and build a resilient infrastructure for future generations. In addition, CSP systems offer dispatchable energy with thermal storage, making them suitable for grid stability and long-term sustainability. These initiatives are part of a comprehensive roadmap that includes regulatory reform, research and development investment, and strategic partnerships with global technology providers.

1.7. Comparison with other renewable technologies

Compared to other renewable energy technologies, such as PV systems and wind power, CSP offers unique advantages. The ability to store thermal energy makes CSP systems more reliable than PV systems, which are limited by the availability of sunlight. Wind power, while also renewable, is subject to variability in wind speeds and requires significant land use. In contrast, CSP systems can be deployed in desert environments with minimal land use conflicts, making them particularly suitable for regions like the MENA region.

The use of sand as a heat transfer medium further distinguishes this CSP system from other renewable technologies. Unlike PV systems, which require expensive semiconductor materials, or wind turbines, which rely on complex mechanical systems, the sand-based CSP system leverages abundant and low-cost materials. This reduces both the capital and operational costs of the system, making it a cost-effective solution for large-scale renewable energy deployment.

2. Methodology

This study evaluated the performance of a CSP system utilizing sand as a heat transfer medium, integrated with a sand–air heat exchanger, a Turbec T100 microturbine generating 100 kWe, and a thermal energy storage system with a capacity of 300 kW thermal. The methodology encompasses the system design, operational testing, data collection, and analysis of economic and environmental impacts, focusing on fuel consumption and CO_2 emission reductions during peak solar hours (9 AM–3 PM) in July.

2.1. System design

The CSP system comprises several key components designed to optimize solar energy capture and conversion, as shown in Figure 3.

Solar collectors (Heliostats) are an array of heliostats installed in 2009 that concentrate solar radiation onto a central receiver. The heliostats, covering an area of 100 m^2, track the sun's movement to maximize DNI capture, typically ranging from 800 to 1000 W/m^2 in Riyadh during July.[7] The PHR collects concentrated solar energy and heats sand particles to temperatures exceeding 600°C.[8] The receiver is designed to handle high-temperature particle flows, ensuring efficient heat transfer to the sand.

The sand–air heat exchanger transfers heat from the hot sand to compressed air, which drives the microturbine.[9] The exchanger is engineered to minimize heat losses, achieving a heat transfer efficiency of approximately 85%. The Turbec T100 Microturbine converts thermal energy from the heated air into electrical power, producing 100 kWe. Its compact design is suitable for small-scale CSP applications.

The storage system, with a capacity of 300 kW thermal, stores excess heat in hot sand for use during non-sunny periods, enabling continuous operation.[10] The storage medium maintains temperatures above 500°C for up to 8 h.

2.2. Data collection

Operational data were collected during July; eight tests were conducted on different days, focusing from 9 AM to 3 PM (6 h or 360 min), when solar radiation is at its peak. Fuel consumption was measured under two conditions: "on-sun" (with solar input) and "off-sun" (without solar input). The fuel flow rate was recorded using a high-precision flow meter, calibrated to an accuracy of ±0.01 L/min. The average DNI was monitored using a pyrheliometer, ensuring accurate solar input measurements. CO_2 emissions were estimated by the emission factor of 2.68 kg CO_2 per liter of fuel, based on standard combustion data.[11]

3. Results

3.1. Fuel consumption analysis

The fuel consumption analysis compared on-sun and off-sun operations, considering the uncertainty of fuel counter measurements, as shown in Figure 4.

During off-sun operation, without solar input, the system relied entirely on fuel, with an average fuel flow rate of 0.47 L/min and with consideration to measurement uncertainty ±0.01 L/min. Over 360 min, total fuel consumption was calculated as 0.47 ± 0.01 L/min × 360 min = 169.2 ± 3.6 L.

During on-sun operation, with solar input, fuel consumption varied hourly, as shown in Table 1. The average fuel flow rate during the period is 0.375 ± 0.01 L/min,[12] resulting in a total consumption of 0.375 ± 0.01 L/min × 360 min = 135 ± 3.6 L. The fuel savings are calculated as 169.2 L – 135 L = 34.2 ± 3.6 L, corresponding to a 20.21% reduction.

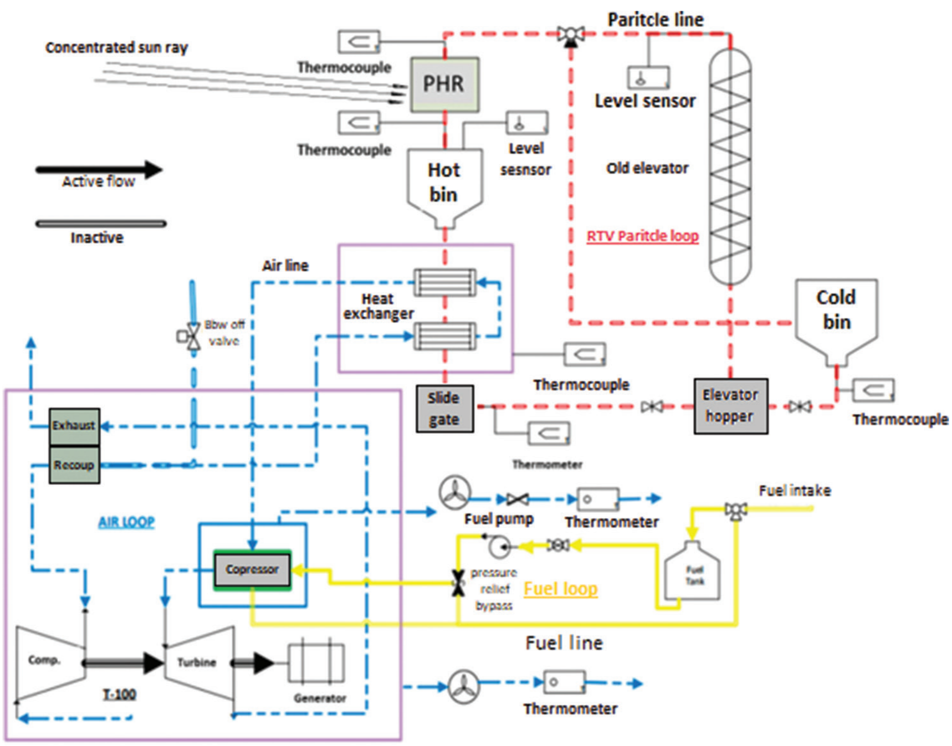

Figure 3. Sand-based concentrated solar power schematic. Reprinted from Alaqel *et al.*[10]
Abbreviations: PHR: Particle heating receiver; RTV: Riyadh Techno Valley.

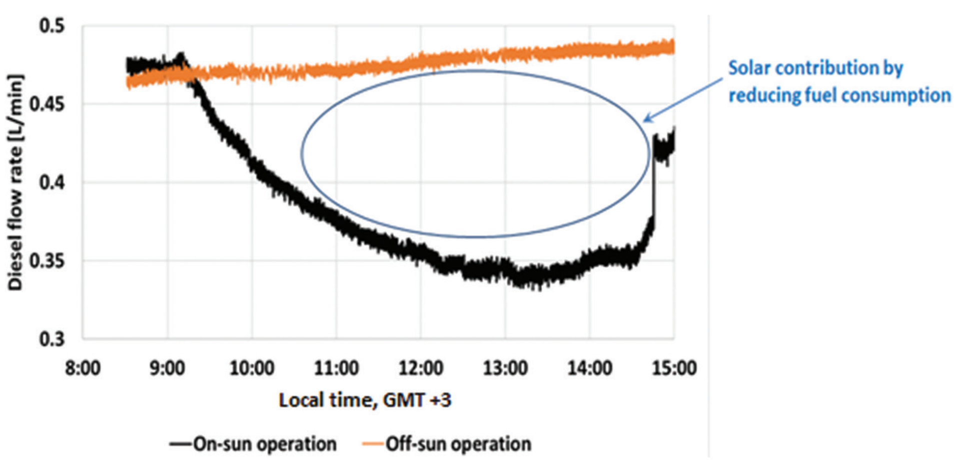

Figure 4. Fuel consumption during on-sun and off-sun operations

Table 1. Fuel consumption during on-sun operation with solar input

Time	09:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00
Fuel consumption L/min with uncertainty±0.01	0.46±0.01	0.38±0.01	0.35±0.01	0.34±0.01	0.35±0.01	0.37±0.01

3.2. Carbon dioxide emission analysis

The conversion factor is a rough estimate for fuel, which produces about 2.68 kg of CO_2 per liter burned (this can vary slightly depending on the fuel's composition). Before CSP, the CO_2 emissions are calculated as 169.2 ± 3.6 L × 2.68 kg/L = 453.46 ± 9.6 kg. After CSP, the CO_2 emissions are calculated as 135 ± 3.6 L × 2.68 kg/L = 361.8 ± 9.61 kg.

Carbon dioxide emission reduction is calculated as 453.46 kg − 361.8 kg = 91.66 ± 13.5 kg. The percentage reduction in CO_2 is calculated as (91.66 ± 0.98 kg/453.46 ± 4.5 kg CO_2) × 100 ≈ 20 ± 0.29 %. Since CO_2 emissions are directly proportional to fuel consumption, the percentage reduction in CO_2 is the same as the percentage reduction in fuel. Due to technological advancements, the impact of uncertainties in modern devices, such as fuel consumption meters and thermocouples, is minimal, with negligible error margins.

3.3. Performance factors

Several factors can influence the system's performance. Higher DNI levels increase solar contribution, making Riyadh's DNI optimal for CSP applications.[13] Regarding the heliostat condition, degradation since 2009 has reduced reflectivity, impacting efficiency, while in terms of heat exchanger design, the sand–air exchanger's efficiency is critical for energy transfer:

> A novel particle-to-air heat exchanger has a patented design with a shell-and-tube configuration.[14] Solid particles move as a dense-packed bed inside the vertical tubes of the heat exchanger, whereas air flows on the shell side.

This design avoids several limitations associated with state-of-the-art heat exchangers in the same category, such as stagnant/void zones and prolonged residence time. The heat exchanger has a 50-kW thermal duty; it has been integrated into the particle-based concentrating solar power facility at the King Saud University campus in Riyadh, Saudi Arabia.

The measurement accuracy was verified by repeating several tests; a slight variation was observed in the measured overall heat transfer coefficient. Table 2 shows the heat exchanger design parameters, and Figure 5 shows the experimental performance of the heat exchanger. It is not possible to assess the heat exchanger performance, as the on-sun tests vary due to fluctuating particle inlet temperatures caused by variable solar flux (DNI).

Table 2. Heat exchanger design conditions

Metric	Value	Unit
Thermal duty	50	kW
Design pressure	3	Barg
Particle inlet temperature	650	°C
Particle outlet temperature	582	°C
Air inlet temperature	540	°C
Air outlet temperature	607	°C
Air flow rate	0.707	kg/s
Particle flow rate	0.7	kg/s

Table 3. Levelized cost of energy of different technologies

Technology	LCOE (2023) (USD/kWh)	Year-on-year LCOE change (2022–2023)
CSP using sand	0.04	-
CSP using molten salt	0.117	−4%
Solar photovoltaic	0.044	−12%

Abbreviations: CSP: Concentrated solar power; LCOE: Levelized cost of energy; USD: United States Dollars.

In addition, sand's thermal conductivity and stability can affect performance, with ongoing studies trying to identify optimal sand properties.

3.4. Technological comparison

This unique system, including the heat exchanger, PHR, thermal battery storage, and other components, has been designed and manufactured to maximize the use of abundant local resources such as sunlight and sand, while focusing on reducing costs compared to technologies currently available in the market. Table 3 illustrates a comparison of the levelized cost of energy (LCOE).[15]

3.5. Summary of results

The results combined system design, operational testing, and data analysis to evaluate the economic and environmental benefits of the CSP system. The prototype's performance during peak solar hours demonstrates its potential, with plans for Phase 2 to address limitations and increase solar contribution to 80%.

4. Discussion

The results of this study demonstrate the significant potential of a sand-based CSP system to reduce fuel

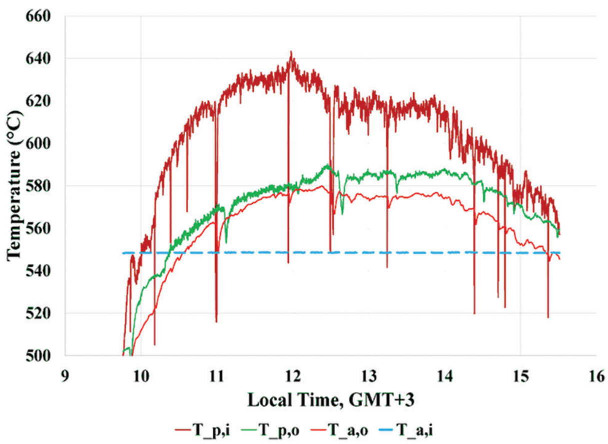

Figure 5. Air and particle temperatures across the heat exchanger during an on-sun test. T_p,i, T_p,o, T_a,o, and T_a,i represent the temperature of particles and air in and out, respectively. Reprinted from Saleh *et al.*[18]

consumption and CO_2 emissions, offering economic and environmental benefits. The prototype, tested during peak solar hours (9 AM–3 PM) in July, achieved a 20% reduction in fuel consumption, from 169.2 L in off-sun conditions to 135 L in on-sun operations, corresponding to a 91.66 kg reduction in CO_2 emissions. These findings align with the broader goals of renewable energy adoption, particularly in regions with high solar potential like Saudi Arabia. This section discusses the implications of these results, compares them with existing literature, and explores the system's scalability and limitations. The 20% reduction in fuel consumption highlights the system's ability to leverage solar energy effectively, reducing reliance on fossil fuels. Compared to traditional CSP systems using molten salts, the sand-based system offers cost advantages due to the abundance and low cost of sand. Studies on molten salt-based CSP systems report similar fuel savings but higher operational costs due to material expenses and corrosion issues. Using sand mitigates these challenges, as it is thermally stable at high temperatures and does not require complex systems. However, the turbine's thermal efficiency of 39.5% is lower than that of some advanced CSP systems, which can achieve efficiencies above 50%. This gap is partly due to heliostat degradation, as the units installed in 2009 have reduced reflectivity, impacting solar capture efficiency. The thermal energy storage component, with a capacity of 300 kW thermal, is a critical feature, enabling the system to operate during non-sunny periods. This capability addresses a key limitation of solar energy—intermittency—and positions the system as a viable alternative to conventional power plants. Compared to battery storage systems, thermal storage using sand is more cost-effective and scalable, particularly in desert environments where sand is abundant.[16] The ability to store heat for up to 8 h enhances the system's dispatchability, making it suitable for meeting peak electricity demands. Economically, the fuel savings translate to reduced operational costs, critical for large-scale adoption. In Saudi Arabia, where energy subsidies have historically driven high fossil fuel consumption, integrating CSP systems could support Vision 2030's goal of diversifying the energy mix.[17] The system's reliance on locally sourced sand further reduces costs, eliminating the need for imported materials like molten salts. However, a detailed cost–benefit analysis, including capital and maintenance costs, is needed to fully quantify the economic viability. Environmentally, the 20% reduction in CO_2 emissions aligns with global sustainability targets, such as those outlined in the Paris Agreement. While the current prototype operates on a small scale, scaling the system could amplify these benefits, potentially achieving an 80% solar contribution as projected for Phase 2. This would result in even greater emission reductions, supporting efforts to combat climate change. Limitations of the prototype include heliostat degradation, which reduces solar input, and the need for optimized sand selection to enhance heat transfer efficiency. Future improvements should focus on advanced heliostat materials and designs to improve reflectivity and durability. In addition, the heat exchanger's efficiency could be enhanced through design modifications, such as increasing surface area or improving particle flow dynamics. These improvements are critical for achieving the projected 80% solar contribution in Phase 2.

In summary, the sand-based CSP system offers a promising pathway for sustainable energy production, with significant economic and environmental benefits. Its scalability, cost-effectiveness, and alignment with regional energy goals make it a compelling solution for sun-rich regions. Further research and development are needed to address technical limitations and optimize system performance.

4.1. Challenges and recommendations

The development and testing of the sand-based CSP system have demonstrated its potential as a sustainable energy solution, but several challenges must be addressed to enhance its performance and scalability. This section outlines the key technical and operational challenges encountered during the prototype testing and provides recommendations for future improvements to achieve the projected 80% solar contribution in Phase 2.

4.2. Technical challenges

4.2.1. Heliostat degradation

The heliostats, installed in 2009, have experienced reduced reflectivity due to dust accumulation and material wear, lowering the system's solar capture efficiency. This degradation is particularly significant in desert environments, where sand and dust storms are common.

4.2.2. Heat exchanger efficiency

The sand–air heat exchanger, while effective, experiences heat losses that limit overall system efficiency. Current designs achieve 85% heat transfer efficiency,[18] but improvements are needed to minimize thermal losses.

4.2.3. Sand properties

The thermal conductivity and stability of the sand used affect heat transfer performance.[19] Variations in sand particle size and composition can lead to inconsistent heating and flow dynamics.

4.2.4. System integration

Integrating the PHR, heat exchanger, microturbine, and thermal storage requires precise control to optimize energy flow and minimize losses.[20]

4.3. Operational challenges

4.3.1. Maintenance requirements

The harsh desert environment necessitates frequent cleaning and maintenance of heliostats to maintain performance, increasing operational costs.

4.3.2. Scalability constraints

The prototype operates on a small scale (100 kWe), and scaling to larger capacities may introduce sand handling and system control complexities.

4.4. Recommendations

To address these challenges and enhance the system's performance, the following recommendations are proposed:

(i) Advanced heliostat designs: Implement next-generation heliostats with improved reflectivity and dust-resistant coatings to enhance durability and reduce maintenance needs
(ii) Optimized heat exchanger: Redesign the sand–air heat exchanger to increase surface area and improve particle flow, targeting a heat transfer efficiency above 90%
(iii) Sand selection studies: Conduct comprehensive studies to identify sand types with optimal thermal properties, such as high conductivity and stability at temperatures above 600°C
(iv) Control systems: Develop advanced control algorithms to optimize the integration of system components, ensuring seamless energy transfer and storage
(v) Scalability planning: To support Phase 2 implementation, perform feasibility studies for large-scale deployment, including cost-benefit analyses and infrastructure requirements
(vi) Regional adaptation: Tailor the system design to leverage Saudi Arabia's high DNI and abundant sand resources, aligning with Vision 2030's sustainability goals.[21]

By addressing these challenges and implementing the recommended improvements, the sand-based CSP system can achieve higher efficiency, greater scalability, and enhanced economic and environmental benefits, paving the way for widespread adoption in sun-rich regions.

5. Conclusion

This study demonstrated the viability of a sand-based CSP system as a sustainable energy solution, achieving significant economic and environmental benefits. By integrating locally sourced sand as a heat transfer medium with a sand–air heat exchanger, a Turbec T100 microturbine, and a 300 kW thermal storage system, the prototype achieved turbine thermal efficiency of 39.5% and reduced fuel consumption by 20% during peak solar hours (9 AM–3 PM) in July. This reduction, from 169.2 L to 135 L, resulted in a corresponding 20% decrease in CO_2 emissions (91.66 kg), highlighting the system's potential to lower operational costs and mitigate climate change impacts.

The incorporation of thermal energy storage enhances the system's reliability, enabling power generation during non-sunny periods and addressing the intermittency of solar energy. The use of sand, an abundant and low-cost material, positions this system as a cost-effective alternative to traditional CSP systems relying on molten salts or synthetic oils. The prototype's performance, reaching technology readiness level 7 in 2018, underscores its readiness for further development and potential large-scale deployment.

Phase 2 of the project aims to increase the solar contribution to 80%, significantly amplifying the economic and environmental benefits. This will require addressing challenges, such as heliostat degradation, heat exchanger efficiency, and sand property optimization. The system's alignment with Saudi Arabia's Vision 2030, which emphasizes sustainable energy and economic diversification, enhances its relevance in the regional context. By leveraging local resources and high DNI levels, the sand-based CSP system offers a scalable model for sun-rich regions, contributing to global sustainability goals outlined in frameworks like the Paris Agreement.

This study provides a foundation for future research on sand-based CSP systems. Key areas for further investigation include optimizing sand properties, such as thermal conductivity and particle size, to enhance heat transfer efficiency. Advances in heliostat design and materials could also improve system performance by reducing degradation and increasing solar contribution. In addition, research into scalable thermal storage solutions could extend the system's ability to provide power during non-sunny periods, further improving its reliability.

The economic and environmental benefits of the system also warrant further exploration. Future studies could focus on the long-term cost savings and emission reductions achievable through large-scale deployment. Integrating sand-based CSP systems with other renewable technologies, such as PV or wind, could also be explored to create hybrid systems that maximize energy output and reliability.

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Conflict of interest

The authors declare they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data analyzed in this study can be accessed through the CSP project control center in King Saud University.

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