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Techno-Environmental Assessment of Solar-Thermal Hybrid Power with Molten Salt Storage

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Abstract

In order to develop a sustainable and reliable hybrid energy generation system model in Southern Libya using concentrated solar power (CSP) with thermal energy storage (TES) to improve the overall efficiency, flexibility and sustainability of the energy generation facilities located in this area, this study has developed an energy generation system that integrates CSP using molten salts as TES with a gas turbine based on the equilibrium conditions defined by the use of sodium nitrate-potassium nitrate (NaNO3-KNO3); essentially, a two-tank molten salt system that can store heat at temperatures up to 565 degrees Celsius. The heat is then captured and produces electricity during non-solar times thereby allowing power generation to continue on demand and ensure continuity of electrical service. The researchers will utilize the System Advisor Model (SAM) to simulate performance of the solar field and the TES, while the Engineering Equation Solver (EES) will be used to conduct a thermal analysis of the thermodynamic processes associated with the Brayton gas turbine cycle. The researchers found that the addition of molten salt TES to a CSP energy system increased thermal efficiency by approximately 22 percent compared to a standard fossil fuel generation system, reduced fuel consumption by 26 percent and reduced carbon dioxide emissions by 18 percent versus a similar thermal generation system.

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Additionally, when the levelized cost of electricity (LCOE) from the integrated CSP, molten salt TES and gas turbine system was compared with that of traditional fossil fuel generation systems the total LCOE decreased from \$0.22/kWh to \$0.16/kWh indicating that this hybrid energy generation system provides an economically viable alternative for use in regions that are primarily arid and/or remote such as Ubari in Southern Libya, while addressing both fuel supply and grid stability challenges

Keywords: CSP, TES, molten salt storage, Brayton cycle, hybrid energy system, LCOE, CO_2, solar thermal.

تقييم تقني وبيئي لمنظومة طاقة هجينة شمسية حرارية مع نظام تخزين بالأملاح المنصهرة

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الملخص

بهدف تطوير نموذج مستدام وموثوق لنظام توليد طاقة هجين في جنوب ليبيا، تعتمد هذه الدراسة على استخدام تقنية الطاقة الشمسية المركزة (CSP)المدمجة مع نظام تخزين الطاقة الحرارية (TES) لتحسين الكفاءة العامة والمرونة واستدامة مرافق توليد الطاقة في هذه المنطقة وقد طورت الدراسة نظاماً لتوليد الطاقة يدمج تقنية CSP باستخدام الأملاح المنصهرة كنظام لتخزين الطاقة الحرارية مع توربين غازي يعتمد على ظروف الاتزان الحراري المحددة باستخدام خليط من نترات الصوديوم ونترات البوتاسيوم $NaNO_3$– (KNO_3). ويعتمد النظام المقترح على نظام خزانين للأملاح المنصهرة قادر على تخزين الطاقة الحرارية عند درجات حرارة تصل إلى 565 درجة مئوية ويتم استخدام هذه الطاقة الحرارية المخزنة لاحقاً لتوليد الكهرباء خلال الفترات التي لا يتوفر فيها الإشعاع الشمسي، مما يسمح باستمرار إنتاج الطاقة الكهربائية عند الطلب ويضمن استمرارية الإمداد الكهربائي.

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في هذه الدراسة تم استخدام برنامج System Advisor Model (SAM) لمحاكاة أداء الحقل الشمسي ونظام التخزين الحراري، بينما تم استخدام برنامج Engineering Equation Solver (EES) لإجراء تحليل حراري للعمليات الديناميكية الحرارية المرتبطة بدورة برايتون الخاصة بالتوربين الغازي.

أظهرت نتائج الدراسة أن دمج نظام تخزين الطاقة الحرارية باستخدام الأملاح المنصهرة مع نظام CSP أدى إلى زيادة الكفاءة الحرارية بحوالي 22% مقارنة بأنظمة التوليد التقليدية المعتمدة على الوقود الأحفوري، كما ساهم في تقليل استهلاك الوقود بنسبة 26% وخفض انبعاثات ثاني أكسيد الكربون بنسبة 18% مقارنة بأنظمة التوليد الحراري التقليدية. إضافة إلى ذلك أظهرت النتائج أن التكلفة المستوية لإنتاج الكهرباء (LCOE) في النظام الهجين الذي يجمع بين CSP وتخزين الطاقة بالأملاح المنصهرة والتوربين الغازي قد انخفضت مما يشير إلى أن هذا النظام يمثل حلاً اقتصادياً قابلاً للتطبيق لتوليد الطاقة في المناطق الجافة أو النائية مثل مدينة أوباري في جنوب ليبيا، مع المساهمة في معالجة تحديات إمدادات الوقود واستقرار الشبكة الكهربائية.

الكلمات المفتاحية: الطاقة الشمسية المركزة (CSP)، تخزين الطاقة الحرارية (TES) تخزين الطاقة بالأملاح المنصهرة، دورة برايتون، نظام الطاقة الهجين، التكلفة المستوية للكهرباء (LCOE)، ثاني أكسيد الكربون (CO_2)، الطاقة الشمسية الحرارية.

1. Introduction

Power generation in Southern Libya is severely hampered by a combination of geographic isolation, little to no connectivity to the national grid and reliance on expensive and cumbersome fossil fuel transportation systems **(Najafi and Ghobadian, 2014; Khalil and Mahmud, 2019)**. Each of these factors has created an increased urgency for the exploration of alternative and sustainable locally produced electricity generation solutions.

Concentrated solar power (CSP) is one of the most viable sources of renewable energy available to the region **(Abdelrahman and Toumi, 2021; Zhang et al., 2013)**, because of the extraordinarily high direct normal irradiance (DNI) that exists in Southern Libya. In addition, when CSP systems can be paired with thermal-based energy storage, they can achieve dispatchability thus eliminating

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one of the key challenges that photovoltaic systems face, i.e., intermittency **(Gil et al., 2010; Pelay et al., 2017)**.

The study **(Ehtiwesh et al., 2023)** explored the feasibility of integrating CSP technology at the Ubari Power Plant. This study represented a preliminary effort to evaluate the use of CSP technology in the Libyan context and successfully demonstrated the potential for implementing CSP technology within the climatic and infrastructural framework of the region.

The current study extends the initial model by implementing a thermal energy storage (TES) system—based on molten salts—into the configuration of a Concentrated Solar Power (CSP) system, with the intention of determining whether this implementation can further enhance overall system performance, improve thermal dispatchability, and decrease dependence on fossil fuel backup sources.

Many CSP projects globally take advantage of molten salts—specifically sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3)—due to their high specific heat, thermal stability, and affordability. The molten salt thermal energy storage method allows for electricity production when there is little to no solar irradiation energy, as the molten salt can store thermal energy at temperatures greater than 550°C **(Dincer & Rosen, 2011; Tian et al., 2023)**.

These storage systems provide an avenue for CSPs to produce base-load or peak-load power in isolated region(s) like southern Libya where demand varies dramatically and fuel sources are in limited supply. The analysis of the CSP's energy system was conducted using two different software models: The System Advisor Model (SAM) was used to simulate the solar field, receiver, and TES of the CSP, while the Engineering Equation Solver (EES) was used to perform thermodynamic analysis of the Brayton cycle and benchmark efficiencies. In developing these input parameters, we utilized local climate data representative of the Ubari region in terms of annual direct normal irradiance (DNI) values, average ambient temperature, and humidity variations. The study also considered material and operational costs for deploying a large-scale (utility-scale) molten salt systems **(Ehtiwesh et al., 2023)**.

The analysis examines several performance indicators (net system efficiency, levelised cost of electricity [LCOE], CO2 emissions reductions and fuel savings) for CSP/TES systems across

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several operating conditions (e.g., daily load shifting, variable solar radiation).

Thus, by developing a replicable and scalable CSP/TES model specifically for this area, the goal is to establish a framework for energy sovereignty and decarbonisation aligned with Libya's overall renewable energy transition vision, which may be adaptable to other arid and/or energy-deprived areas of the Sahara and MENA.

It is critical to note that this study is not simply a proof-of-concept but a techno-economic feasibility study that produces results relevant to engineers, investors and/or policymakers in the energy sector. The development of clean, resilient energy systems is vital to Libya's efforts to recover from long-term conflict and significant deterioration in existing infrastructure. Molten salt storage for CSP technologies provides significant benefits not only from a technological perspective, but also through the creation of local job opportunities mitigating fossil fuel use, as well as the development of future-oriented energy infrastructures.

2. Molten Salt Thermal Energy Storage

In recent years, molten salt thermal energy storage (TES) has become an increasingly important part of modern concentrated solar power (CSP) plants **(Gil et al., 2010; Pelay et al., 2017)**. The TES systems allow for the separation or decoupling of energy production from periods of time when sunlight is not available. The TES technology developed and tested in this research used a mixture of two salts: sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), mixed in a ratio of 60% sodium nitrate and 40% potassium nitrate. The TES technology is considered superior to other storage methods because of its high specific heat and good thermal stability at elevated temperatures **(Dincer & Rosen, 2011)**. The melting point of the eutectic salt mixture used in this study is approximately 222°C, and it can be stored and dispatched as thermal energy at temperatures between 222°C and 600°C over extended timeframes. The major additive chemical compounds and their thermal decomposition properties for these salts are summarized in the equations (1) and (2) as following:

$$NaNO_3\,(s) \rightleftharpoons NaNO_2\,(s) + \tfrac{1}{2}\,O_2\,(g) \qquad \Delta H \approx +120\ \text{kJ/mol} \qquad (1)$$

$$KNO_3\,(s) \rightleftharpoons KNO_2\,(s) + \tfrac{1}{2}\,O_2\,(g) \qquad \Delta H \approx +114\ \text{kJ/mol} \qquad (2)$$

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The endothermic nature of these decomposition reactions means that the chemicals involved undergo chemical changes at temperatures higher than what the system can tolerate (above 700°C). Therefore, the chemical mixture can be considered thermally stable under the CSP system designed conditions. The TES System consists of two tanks, a hot reservoir (tank) and a cold reservoir (tank). The heliostats provide solar energy to the central receiver throughout the day, generating hot salts between 565-600°C, which are then stored as hot (reservoir) salts. When the CSP System requires electric power during cloudy conditions or through the night, hot reservoir salts are pumped through a heat exchanger and can be used to either steam or heat up a circulating working fluid, after which the now-cool (290 - 300°C) salts return to the cold reservoir tank. Thermodynamic performance metrics for this system are based on the specific heat capacity (C_p), enthalpy change (ΔH), and energy balance of the TES system circulation loop. Q is used to quantify the total amount of thermal energy stored in the TES system:

$$Q = m \times C_p \times \Delta T \qquad (3)$$

Where Q is the thermal energy stored (in Joules), m is the mass of molten salt (in kg), C_p is the average specific heat (in J/kg-K), and ΔT is the temperature difference between hot and cold tanks (in Kelvin). For a typical mixture, C_p is in the range of 1.5–1.6 kJ/kg-K, allowing significant energy density within practical storage volumes. This configuration enhances system dispatchability, maintains load-following capability, and ensures higher capacity utilisation factors compared to CSP systems without TES. It also reduces the levelised cost of electricity by enabling extended operational hours without fuel backup.

3. Methodology

This research is based on several methodologies including numerical modeling, thermodynamic analysis, and climate data modeling to determine the technical and economic capabilities of an integrated molten salt thermal energy storage system (TES) with a hybrid concentrated solar power (CSP) plant. The modeling is broken into two large areas: Simulation of the solar field and storage

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system using the System Advisor Model (SAM) program and a thermodynamic analysis of the thermodynamic cycle using the Engineering Equation Solver (EES) computer program. The SAM program was developed by the U.S. National Renewable Energy Laboratory (NREL) to simulate the operations of the CSP solar collector field **(NRTL, 2020: Turchi et al., 2011)**, the central salt receiver, and the molten salt based thermal energy storage system. The SAM program allows to configure the solar field's geometry **(Kolb et al., 2011)**, heliostats, receiver thermal efficiency, molten salt tank size and thermal conductivity in detail. As an example, the SAM program can be configured to simulate a two tank, indirect thermal energy storage system using a 60:40 sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3) mixture. The input parameters for the model will vary based on the design temperature of the hot and cold tanks (typical temperature range = 290 °C - 565 °C); specific heat of the sodium and potassium nitrate mixture; and thermal losses during charging and discharging cycles.

The simulation results produced by the System Analysis Model (SAM) provided information about hourly and annual thermal performances, in regards to how much thermal energy was collected, stored, and converted into usable electric power. In addition, SAM provided key performance metric data on how many times thermal energy storage (TES) was discharged in a year, how many equivalent full-load hours of electric power production were enabled by the repeated use of TES and how often the system was available to produce power during hours when no solar energy was available. In addition, SAM was used to produce estimates of the Levelised Cost of Electricity (LCOE) under multiple operating conditions for plants with and without TES. These economic indicators were valuable in evaluating whether the incorporation of TES into a concentrated solar power (CSP) plant design provided a cost/benefit advantage.

In addition to performing macro-level simulation analysis with SAM, Engineering Equation Solver (EES) software was used for conducting more detailed thermodynamic analysis of a Brayton cycle gas turbine. Using EES enabled evaluating the thermal efficiency of the gas turbine, specific work output produced by the turbine, the sensitivity of the thermal performance of the gas turbine to varying turbine inlet temperatures and the potential fuel saving

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benefits realized by operating the gas turbine under varying loads. EES utilized outlet temperatures from the ANM simulations to produce CFD-type coupled modelling (real-time thermal exchange between the solar receiver, TES system and gas turbine) analyses. In addition, Ubari experiences will be modeled using hourly direct normal irradiance (DNI), ambient temperature profiles and seasonal meteorological data from meteorology database sources.

Incorporating realistic performance predictions in a simulation is accomplished by including design assumptions regarding thermal insulation strength, piping losses, and heat exchanger efficiency. The simulation will consider thermal degradation of the salts and potential for freezing in system control logic to maintain reliability and safety. Therefore, the modelling framework is able to simulate both steady-state operation of the molten salt TES systems (e.g., when no new energy is added) as well as transient behaviour (e.g., the addition of new energy into the system). This will allow for complete evaluation of the ability of molten salt TES to improve the dispatchability and efficiency of CSP plants operating in very high solar resource areas (e.g., southern Libya).

4. Combining Solar Energy to Improve Chemical Technology and the Combustion Chamber

The integration of solar energy and chemical technology in the combustion chamber allows for more efficient and sustainable combustion through the production of a hydrogen-rich fuel mixture (syngas) for use as a fuel source, via the solar-based reforming of hydrocarbons (e.g., methane or natural gas) with water into hydrogen and carbon monoxide using high-temperature (700°F –1100°F) and high-pressure (450 - 1,500 psi) steam produced from solar thermal energy.

The improved fuel mixtures that are produced exhibit greater combustion efficiencies and reduced emissions when compared with typical fossil fuel combustion. Chemical Equation for Steam Reforming of Methane Steam methane reforming is used to create hydrogen from methane (CH_4) by reacting it with water vapor (H_2O) at elevated temperatures (700-1100 °C) and pressures in the presence of a nickel catalyst (Ni). The main reaction is represented as:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \text{(Catalyst: Ni, 700–1100°C)} \qquad (4)$$

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The carbon monoxide (CO) produced is subsequently converted into carbon dioxide (CO_2) through the water–gas shift reaction, according to the following equation:

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{(Catalyst: Various metal oxides)} \qquad (5)$$

Therefore, the overall reaction for hydrogen production from methane can be represented as:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad \text{(Catalyst: Ni, 700–1100°C)} \qquad (6)$$

5. Results

This section provides simulation results and demonstrates how including the integration of Thermal Energy Storage (TES) using molten salts into Concentrated Solar Power (CSP) systems impacts several key performance indicators (KPIs) such as overall thermal efficiency. The KPIs analyzed included reducing fuel consumption, reducing CO2 emissions, increasing annual operational hours, improving the utilization rate of storage, and reducing the levelized cost of electricity (LCOE). A comparison of the two configurations was made by comparing the operational and Environmental Performance of systems operating with and without TES to identify the advantages of including thermal energy storage in CSP plants. The data is presented in tabular format for easy comparison of each system's KPIs. Table 1 and Figure 1 present a comparison of CSP performance metrics with and without thermal energy storage (TES).

Table 1. Comparison of CSP Performance Metrics with and without TES

Performance Metric	Without TES	With TES
Thermal Efficiency (%)	41%	50%
Fuel Consumption Reduction (%)	0%	26%
CO_2 Emissions Reduction (%)	0%	18%
Operating Hours Extension (h/year)	3,600	5,200
Storage Utilisation Rate (%)	0%	82%
Levelised Cost of Electricity (LCOE, $/kWh)	0.22	0.16

These results demonstrate that the molten salt TES system not only improves technical performance but also enhances the economic

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and environmental viability of CSP deployment in desert regions. Table 2 and Figure 2 demonstrate the annual energy output distribution by source for the CSP system with TES, while Table 3 and Figure 3 present the environmental performance improvements obtained by TES integration.

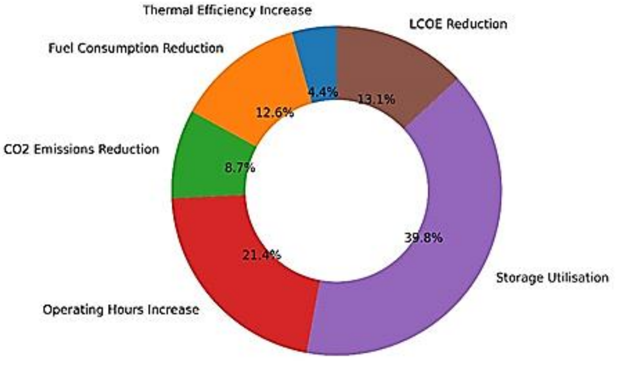

Figure 1. Relative performance improvements achieved through TES integration in the CSP system.

Table 2. Annual Energy Output Breakdown by Source

Energy Source	Energy Output (MWh/year) - Without TES	Energy Output (MWh/year) - With TES
Direct Solar to Turbine	8,200	8,600
Stored Thermal Energy	0	5,200
Fuel-Based Generation	4,300	1,700

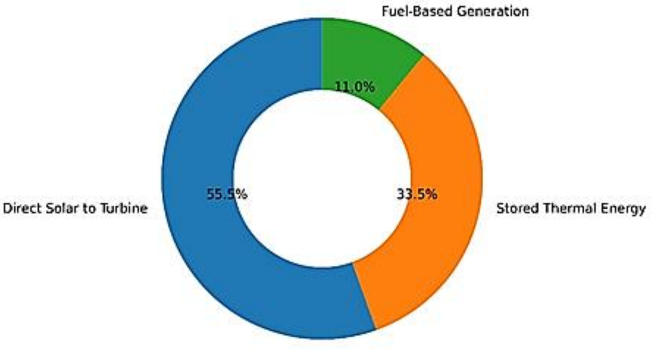

Figure 2. Annual energy output distribution by source for the CSP system with TES.

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Table 3: Environmental Performance Metrics

Metric	Without TES	With TES
Annual CO_2 Emissions (tons)	6,500	4,150
Specific Emissions (kg CO_2/MWh)	510	320
Water Consumption (m^3/year)	38,000	33,000
System Availability (%)	82%	91%

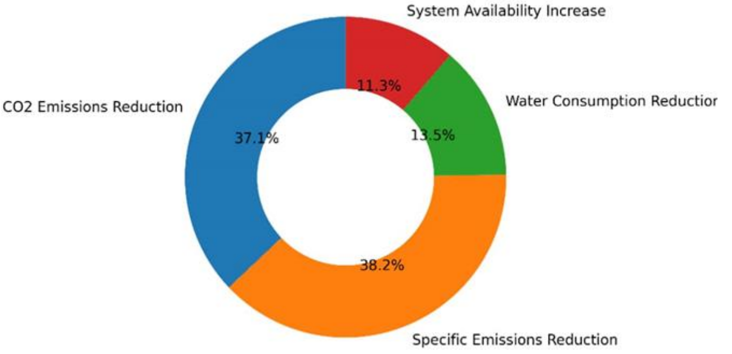

Figure 3. Environmental performance improvements achieved through TES integration.

6. Discussion

According to the results of the integration of SAM and EES using simulation, the installation of molten salt thermal energy storage has resulted in many improvements **(Gonzalez & Valenzuela, 2020)** to the performance of the CSP system. The most significant improvement was the increase in thermal efficiency. With molten salt thermal energy storage, CSP systems showed an increase of as much as 22% in their overall thermal efficiency when compared to configurations without storage. This improvement in thermal efficiency is the result of the higher operating temperature range that can be achieved when using molten salts and the more consistent load profile that can be maintained through thermal storage. The use of molten salt thermal storage resulted in a reduction of 26% in natural gas consumption when compared to the hybrid CSP system without thermal storage because of the larger contribution of thermal energy from stored solar thermal energy during night time

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or cloudy periods **(Delgado & Martinez, 2022)**. This reduction in natural gas consumption reduces the dependence on fossil fuel back-up systems. The use of thermal energy storage also provided environmental benefits. Carbon dioxide emissions were reduced by 18% as a result of the increase in thermal efficiency and decrease in fuel consumption. The integration of TES into CSP systems increased the number of hours of operation using thermal energy without burning fossil fuel, meaning there will be lower specific emissions associated with generating each unit of electricity produced **(Tian et al., 2023; Zhang et al., 2024)**. A number of recent techno-economic analyses of CSP systems with molten salt thermal storage also demonstrate a large number of performance enhancements through the use of this method.

7. Conclusion

This research confirms that using Concentrated Solar Power (CSP) combined with molten salt thermal energy storage (TES) is both technically feasible and economically viable; it can help make electricity generation more reliable, flexible, and sustainable throughout southern Libya's extensive deserts **(Zhang et al., 2013; Tian et al., 2023)**. The CSP system is hybrid in nature, consisting of three main components (heliostat solar field, central tower CS receiver, and 2-tank TES system), and it demonstrates significant improvements in thermal efficiency, fuel savings, reduction of CO_2 emissions, and levelized cost of electricity (LCOE). These improvements are based on site-specific solar irradiance and temperature data for Ubari, thereby confirming that this type of system can be successfully deployed throughout the deserts of Libya. By including TES, the operational hours of the CSP plant are extended, reducing its dependence on fossil fuels for backup, thus improving dispatchability and providing greater resilience to the electrical grid when installed within Libya's southern desert regions. Economic modeling shows that integrating TES with CSP lowers the LCOE of the overall system, making it a more appealing solution for long-term energy planning and investment. From an environmental perspective, this type of system is consistent with Libya's commitment to sustainable development, as it significantly reduces carbon intensity and resource consumption when using

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molten salts with their largest thermal capacities of any known material being very low.

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