SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Solar Resource Assessment

https://doi.org/10.52825/solarpaces.v3i.2290

Published: 27 Aug. 2025

Optimization of Hybrid Renewable Energy System Incorporating Solar Tower With Thermal Energy Storage, PV and Battery Storage for Enhanced Energy Flexibility and Reliability

Maklewa Agoundedemba[1,2], Chang Ki Kim[2,3,*], Hyun-Goo Kim[2,3], Raphael Nyenge[1], and Nicholas Musila[1]

[1]Kenyatta University, Kenya

[2]Korea Institute of Energy Research, Korea

[3]University of Science and Technology, Korea

*Correspondence: Chang Ki Kim, ckkim@kier.re.kr

Abstract. The urgent need for sustainable energy solutions to combat climate change and the growing global energy demand has stimulated the development of renewable energy technologies. Among these, hybrid renewable energy systems (HRES) that combine multiple energy sources promise enhanced efficiency, reliability and flexibility compared to single-source systems. This research focuses on a novel HRES configuration that integrates a concentrated solar power named solar tower with thermal energy storage (TES), photovoltaic modules and battery energy storage systems (BESS) in North Togo. The study aimed to maximize the energy produced, while reducing costs and finally evaluated the environmental aspect saved. We use parametric optimization through SAM to determine the optimum levelized cost of energy and net present value. SAM software was used for heliostat modelling. The single-owner model was used for financial analysis. The results demonstrated the project's financial viability and environmental impact, with an LCOE of $\$0.14kWh^{-1}$ indicating a competitive cost of energy production and an IRR of 14.87% showcasing strong investment returns. A high NPV of $9,307,001 indicated some good interest in the proposed HRES. Furthermore, the significant reduction of 25,815.7513 tons of CO_2 emissions highlights the project's substantial contribution to sustainability and carbon footprint reduction.

Keywords: Solar Tower, Thermal Energy Storage, Heliostats, CSP/TES/PV/Battery Hybrid

1. Introduction

Accessing to electricity is one of the criteria for the prosperity of any country. In West Africa, the situation remains challenging, with an average electricity access rate very low in rural areas, where it is less than 25%[1]. The high cost per kilowatt-hour further exacerbates the issue, delaying economic progress in several regions. For many years, Togo has depended on neighboring countries like Nigeria and Ghana for its electricity supply, highlighting the urgent need for a more sustainable and independent energy solution. Renewable energy technologies have become increasingly critical in addressing global energy demands and combating climate change. These technologies offer viable alternatives to traditional fossil fuels, with hybrid renewable energy systems (HRES) emerging as innovative solutions that improve energy efficiency, reliability and system flexibility[2][3]. Previous studies have primarily focused on single-source renewable energy systems, such as solar or wind, but these often face limitations in efficiency and reliability due to their dependence on a single energy source. The integration of diverse energy generation and storage technologies within HRES enables the exploitation of the complementary characteristics of each component, enhancing the overall performance and economic viability of the energy system.

This study focused on a novel HRES configuration that integrated concentrated solar power (CSP) with thermal energy storage (TES), photovoltaic (PV) modules, and battery energy storage systems (BESS). The primary objective was to minimize the levelized cost of energy (LCOE) and maximize the net present value (NPV). By leveraging the strengths of each component, the system aimed to provide cost-effective and reliable energy. The CSP component, equipped with TES, offers dispatchability, allowing for energy supply even after sunset, while the PV component provides economical energy during periods of high irradiance. The BESS component enhanced system flexibility by managing short-term fluctuations and supplying energy during low sunlight conditions. This research addressed the critical need for efficient and reliable renewable energy solutions, proposing a novel approach that could significantly contribute to the transition to sustainable energy in the northern Togo region. This paper is structured as follows: Section 2 describes the methodology, including the parametric optimization process using SAM. Section 3 presents the results and discussions, while Section 4 concludes the study with key findings.

2. Methodology

2.1 Study area and motivation

The study site is Cinkassé(Figure 1) located near the border with Burkina Faso, a Sahelian country recognized for its high direct normal irradiance (DNI) and strong potential for CSP deployment [4]. Inspired by the 50 MWp PV plant in Blitta, Togo, which electrifies over 158,000 households[5], this study targets a similarly rural context in Cinkassé. A system sized to 28 MW (25 MW CSP + 3 MW PV) is proposed to supply energy for approximately 80,000 households in the Cinkassé region.

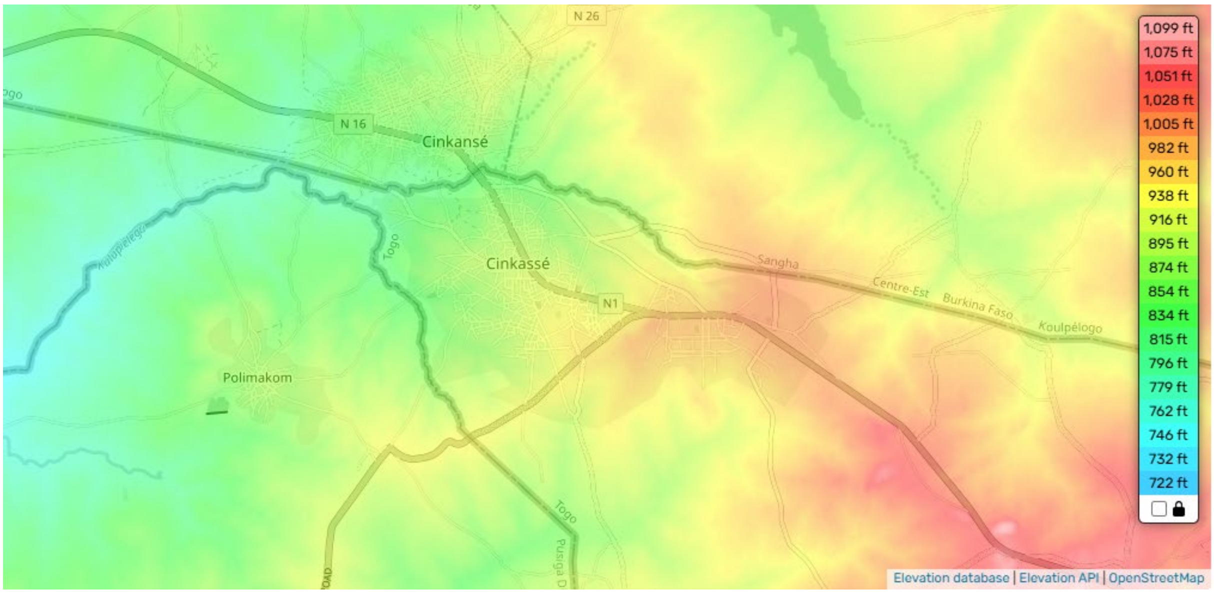

Figure 1. *Location and elevation map of Cinkassé, Togo[6]*

2.2 Solar resource assessment and data preprocessing

Solar and meteorological data were sourced from the National Solar Radiation Database (NSRDB) for the year 2022 at the coordinates 11.100556°N, 0.013333°E. For the Solar Tower, DNI data was used; for the PV/Battery system, GHI, temperature were extracted and wind speed was also ploted. The data was preprocessed using Python (version 3.9.18)[7]. Missing values were interpolated, and data was aggregated into hourly and monthly averages. The DNI threshold of 800 W/m² was chosen based on the 95th percentile (P95) value as shown in Figure 2, meaning this irradiance level is exceeded 5% of the time. This ensures a conservative and reliable design point. Seasonal and diurnal DNI patterns were analyzed using contour-maps, showing high irradiance between 10:00 AM and 2:00 PM during the dry season. The plot of DNI, GHI, temperature and wind speed at the locatiopn study is shown in Figure 3. It was design to reflect approximately the peak hourly load demand of 28 MW.

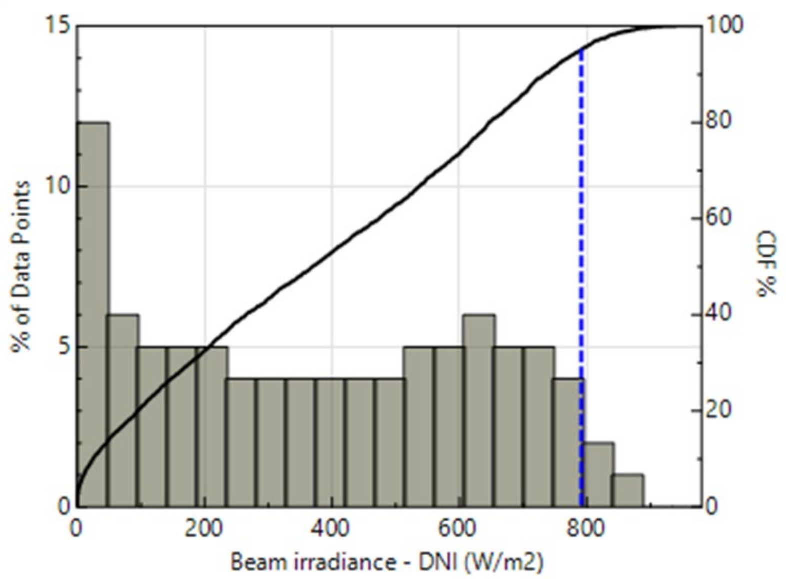

Figure 2. *DNI distribution and cumulative distribution function (CDF) indicating the DNI*

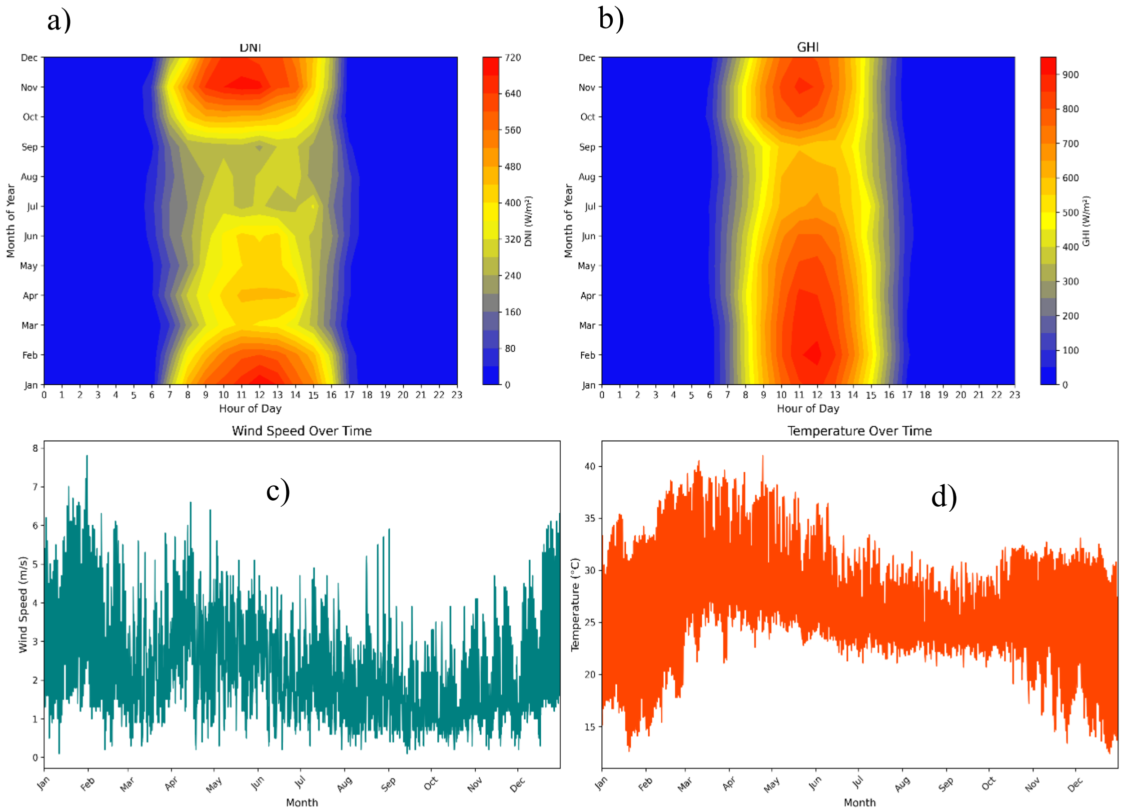

Figure 3. *Hourly and seasonal distribution of a) DNI, b) GHI, c) Wind speed and d) Temperature over the year in Cinkassé, Togo*

2.3 System configuration and design parameters

The hybrid renewable energy system consists of a CSP tower with TES, PV array, and a battery subsystem. The CSP plant was modeled with a turbine gross output of 25MW and 15 hours of thermal storage. The PV system is 3 MWdc. All input used is stated in Table 1. A schematic overview is presented in Figure 4.

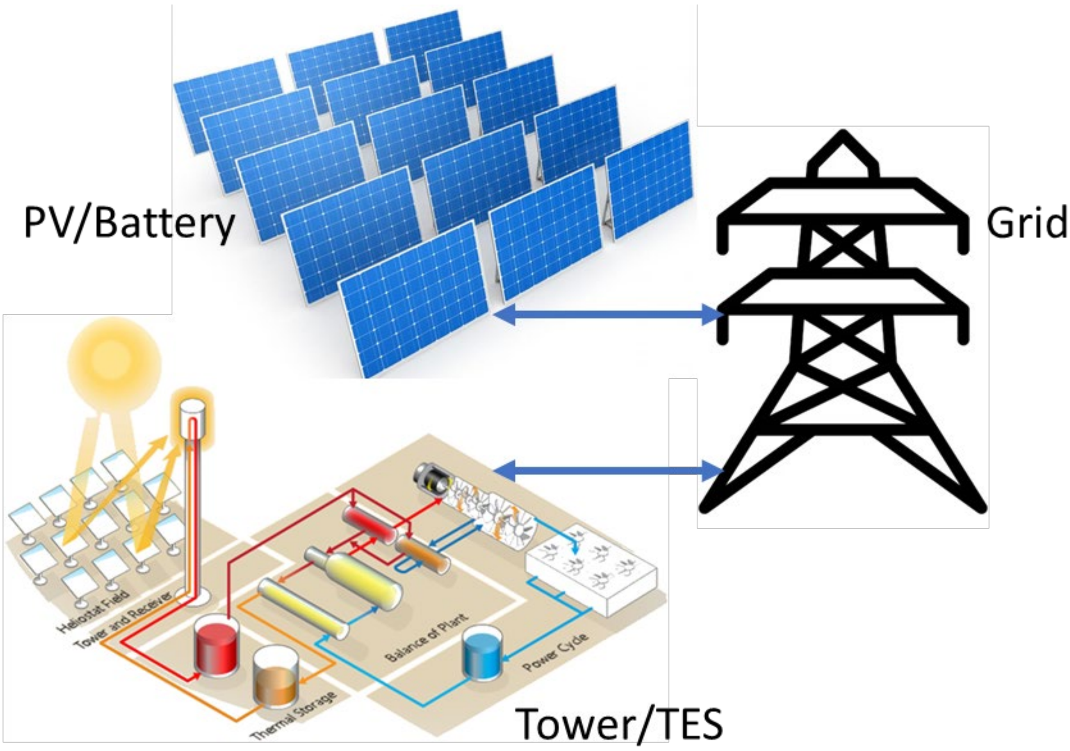

Figure 4. *System Configuration*

2.4 Optimization framework

Parametric sweeps were carried out in SAM[8] to optimize three key CSP parameters: turbine gross output tested from 5 to 75 MW in 5MW increments.Thermal storage hours tested from 4 to 20 hours in 1-hour increments. Solar Multiple (SM) ranged from 1 to 4 in increments of 0.2. The LCOE, NPV and IRR were obtained directly from SAM's built-in financial model single owner model. The LCOE was computed based on total lifecycle costs divided by lifetime energy output, while NPV was calculated as the discounted sum of future net cash flows using a real discount rate of 8%. These financial metrics reflect the project's economic feasibility under the input assumptions outlined in Table 1. The optimal values were used in the final simulation to obtain an optimum LCOE.

Table 1. *Design parameters of solar tower/PV/Battery [8][9][10][11]*

Parameters	Values
HTF cold temperature	290°C
HTF hot Temp	565°C
Full load hour of storage	4h-20h
Solar multiple	1-4
Tower height	95.2m
Receiver height	10.53m
Receiver diameter	10.33m
Number of panels	20
Tube outer diameter	40mm
Thickness of pipe	1.25mm
Surface of heliostat	144.37m^2
Number of Heliostat	2,444
Analysis period	25
Inflation rate	2%
Real discount rate	8%
Thermodynamic efficiency	37%
Heliostat cost	50$/m^2
Receiver reference cost	$62,428,300
Tower cost fixed	1,818,300$
Contingency	2%
EPC	10%
Variable	3$/MWhac
Total Plant installation cost	$85,666,657.21
OM of HRES	15$/KW-year

2.5 PV and battery modelling and carbon dioxide evaluation

The PV and battery output was modeled using PVWatts-Battery model within SAM. Equation used are temperature-corrected performance equations according to [12].

$$P_{PV} = \sum_{t=1}^{8760} \left(Pr_{pv} N_{pv} df\right)\left(\frac{G(t)}{G_{ref}}\right)\left(1 + K_T\left(\left(T_{amb}(t) + G(t) \times \left(\frac{NOCT-20}{800}\right)\right) - T_{ref}\right)\right) \quad (1)$$

The battery charge level is modelled by [13].

$$SOC(t+1) = SOC(t) + \frac{P_c(t).\Delta t.\eta_c}{E_{batt,cap}} - \frac{P_{dc}(t).\Delta t}{\eta_{inv}.\eta_{dc}.E_{batt,cap}} \quad (2)$$

The quantity of the carbon dioxide saved was given by:

$$tCO_2 = EF \,.\, E_{ann} \quad (3)$$

tCO_2 represents the tone of CO_2 savings from the operation of a solar power project, EF is the emission factor which was 0.3834 tCO_2[8] equivalent per MWh generated. E_{ann} represents the annual amount of electricity generated by the plant.

3. Results and discussions

3.1 Sensitivity analysis for CSP parameters

Figure 5 shows NPV vs. turbine gross output. The curve peaks at 11 MW, yielded the best balance of cost, beyond which NPV declines due to oversizing. However by compromising to have high capacity with NPV greater than zero, the capacity of 25 MW was selected. Further sweeps found optimal performance at: solar multiple 1.8 and TES = 15 hours. As shown in Figure 6, the optimum NPV achieved was $1.75858x10^8, with those optimum values. This optimal configuration was a careful balance of the solar multiple and storage capacity to maximize economic returns. A solar multiple of 1.8 indicates that the solar field is 1.8 times larger than what is needed to run the power block at its nominal capacity, ensuring that excess thermal energy is available for storage and use during periods of low solar irradiance. The 15-hour thermal energy storage ensures that the system can supply power consistently, even during the night or cloudy days, thereby enhancing the reliability and dispatchability of the power supply.

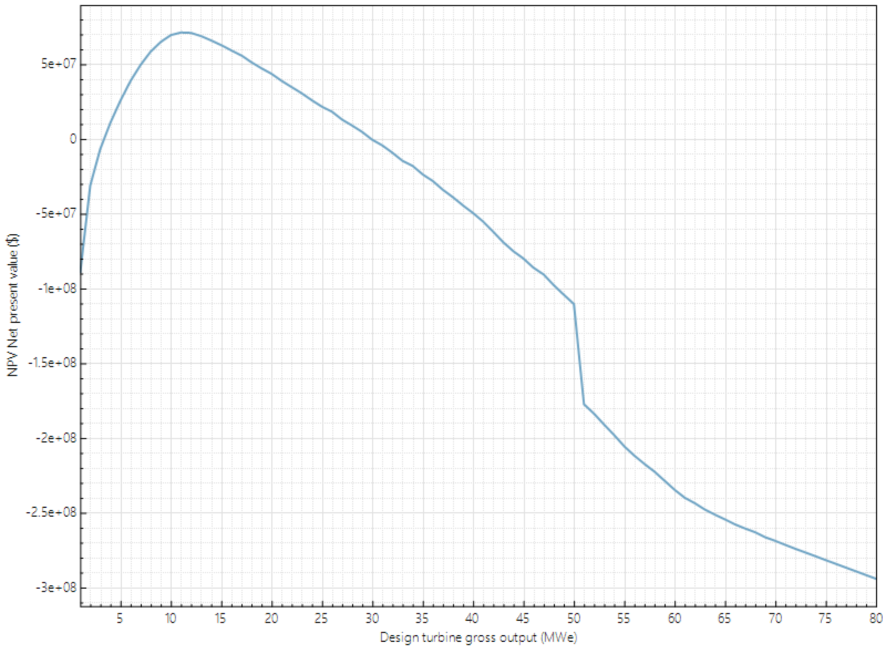

Figure 5. *Sensitivity analysis of NPV versus design turbine gross output for CSP system*

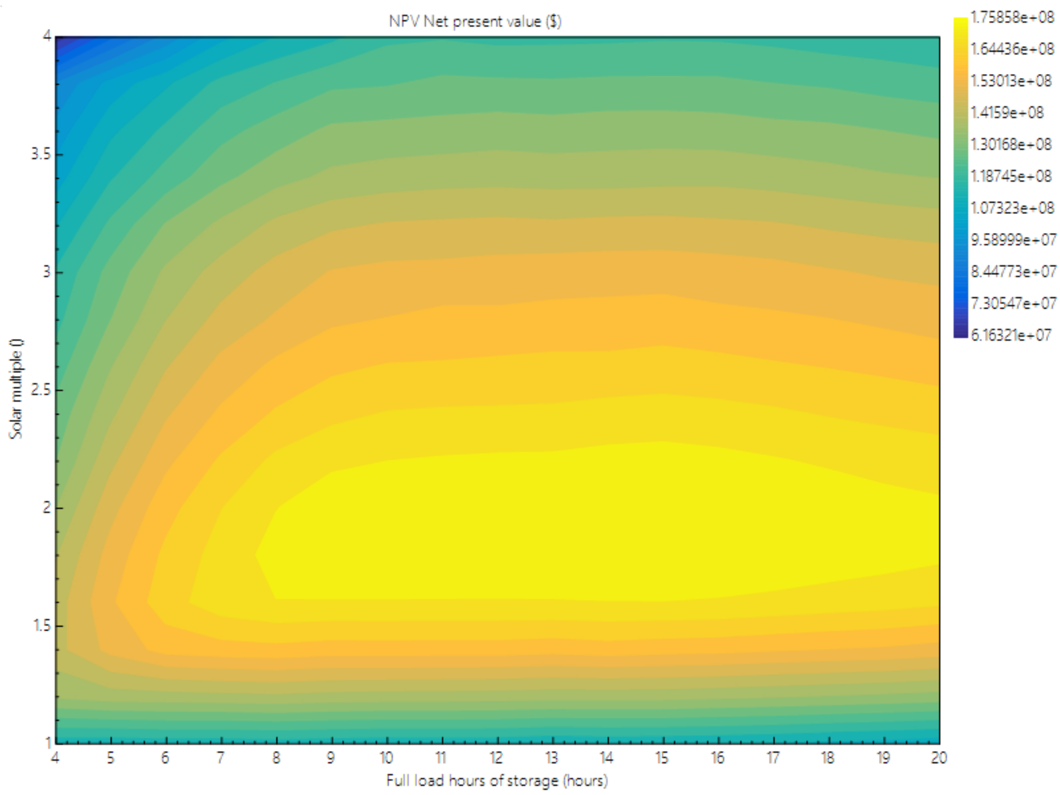

Figure 6. *Variation of net present value with solar multiple and full load hours of storage*

3.2 Energy output and system behavior

Figures 7 and 8 illustrate the annual AC energy production for the Solar Tower/TES and PV/Battery systems, respectively. The PV system contributed primarily during daytime hours between approximately 8:00 AM and 4:00 PM, with its peak generation occurring around midday. During the early morning (12:00 AM to 7:00 AM) and late afternoon through midnight (4:30 PM to 12:00 AM), the PV/battery system's output dropped significantly due to reduced solar resource availability, requiring supplementary energy from the CSP system and, when necessary, grid imports. The Solar Tower/TES system played a critical role in supporting the hybrid system during these non-solar hours and cloudy periods, although its output varied according to thermal storage availability and DNI fluctuations. Furthermore, Figure 9 shows that energy imported from the grid was minimal in comparison to total system output. Annual energy generation reached 67,333,728 kWh, and with grid imported it was 67,740,726.69 kWh. The energy contributions were as follows: CSP 91.98%, PV/Battery 7.40%, and grid 0.60%. As highlighted in Figure 9, grid reliance was highest in August, which corresponds with the rainy season characterized by reduced solar resource availability, cloud cover and potentially increased household electricity use due to longer lighting hours.

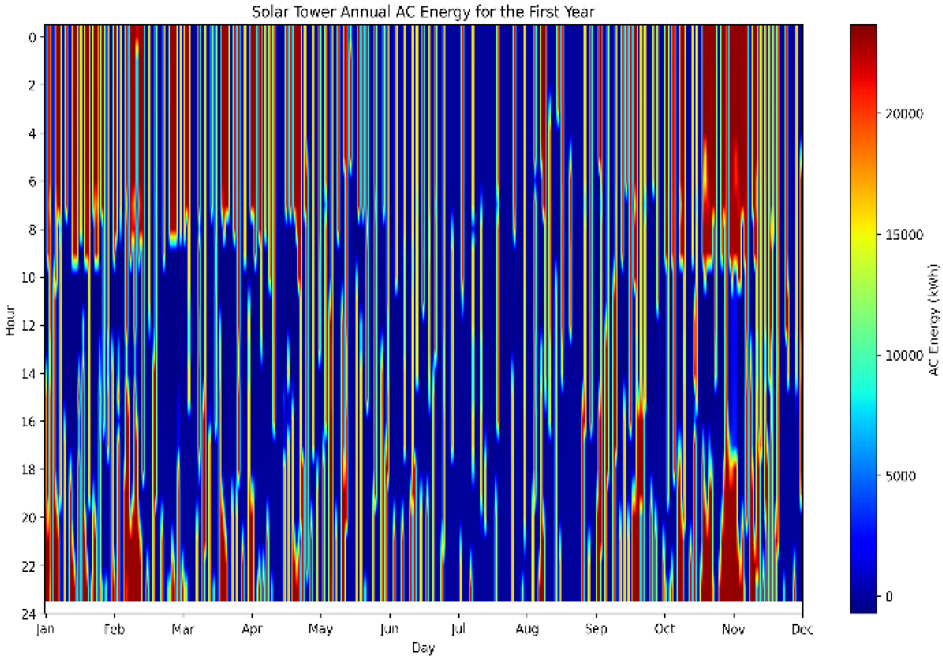

Figure 7. *Solar tower/TES AC energy*

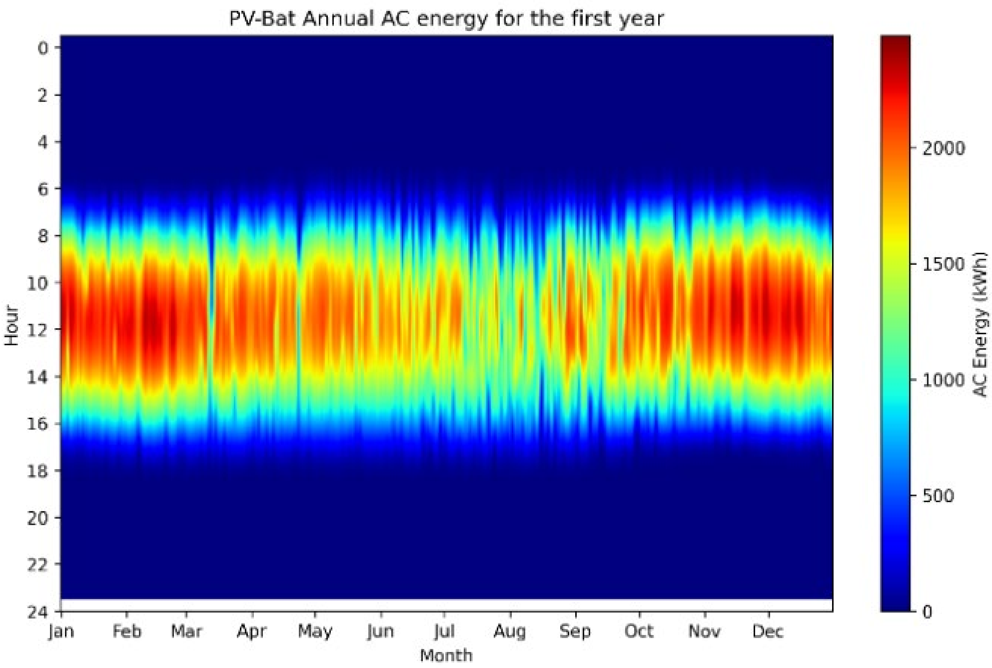

Figure 8. *PV/Battery AC energy*

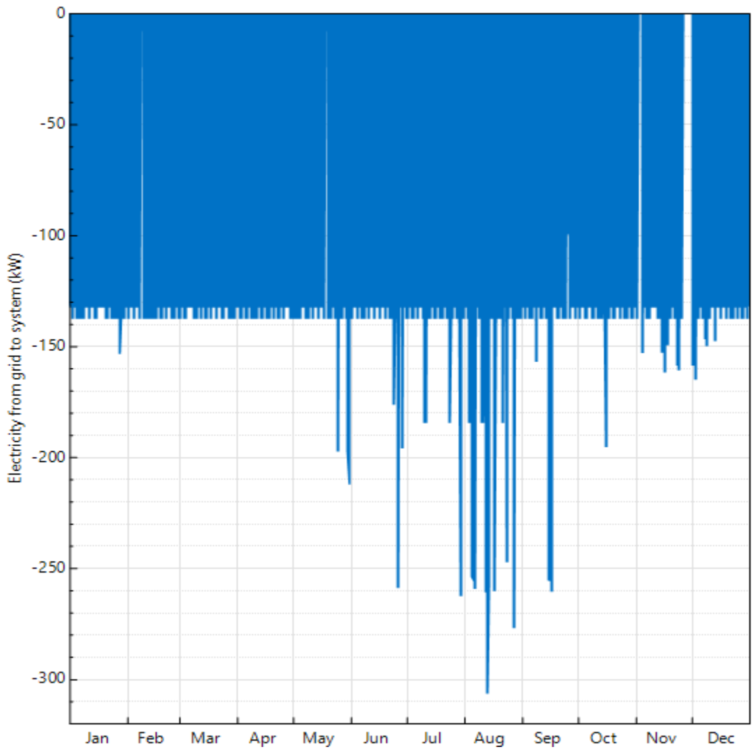

Figure 9. *Electricity from the grid to the System*

3.3 Economic performance and carbon dioxide evaluated

The LCOE and the IRR Internal rate of return at the target year (20th year) and at the end of the project (25th year) found are mentioned in the following Table 2. The LCOE, which represents the average cost per unit of electricity generated, was 14.11 cents per kWh in real terms (accounting for inflation) and 16.80 cents per kWh in nominal terms (without accounting for inflation). The NPV, which measures the total value of future cash flows discounted back to their present value, indicates that the project is expected to generate substantial value over its lifetime. The IRR was 12.48% in the 20th year, rising to 14.87% by the end of the project, indicating a healthy return on investment, where the project is expected to generate returns above the typical cost of capital, thus making it financially viable. The hybrid system achieved estimated carbon dioxide savings of approximately 25,816 tons per year as shown in Table 2.

Table 2. *Project metrics calculated*

Metrics	Values
Real LCOE	0.1411 $\$kWh^{-1}$
Nominal LCOE	0.1680 $\$kWh^{-1}$
NPV	$\$1.75858 \times 10^8$
IRR at 20th year	12.48 %
IRR at end of project	14.87 %
Total AC generated/year	67,333,728 kWh
CO_2 Saved	25,815.7513 tCO_2

4. Conclusion

This study demonstrates the potential of HRES integrating CSP, TES, PV and BESS. The findings indicate that such a system can effectively enhance energy production efficiency and reliability. The parametric optimization through SAM has proven instrumental in determining the optimal capacity, leading to a competitive LCOE of $\$0.14kWh^{-1}$ and a robust IRR of 14.87%.

These results emphasize the financial viability of the project and its investment potential. Additionally, the system's capability to significantly reduce carbon emissions by 25,815.7513 tCO_2 annually highlights its substantial environmental benefits.

Data availability statement

The data cannot be shared due to privacy restrictions.

Author contributions

Data cleaning, Conceptualization, formal analysis, investigation, methodology, validation, visualization, original draft preparation, writing, Maklewa Agoundedemba; Conceptualization, investigation, project administration, review and editing, validation, supervision, Chang Ki Kim and Hyun-Goo Kim; Supervision-review-validation, Raphael Nyenge and Nicholas Musila.

Competing interests

The authors declare no conflict of interest.

Funding

This work was conducted under the framework of the research and development program of the Korea Institute of Energy Research (C5-2422); the Partnership for Applied Sciences, Engineering, Technology, Regional Scholarship, and Innovation Fund (B8501E30178).

Acknowledgement

The authors acknowledge the renewable energy big data laboratory team at Korea Institute of Energy Research, the Partnership for Applied Sciences, Engineering, and Technology (PASET) and Regional Scholarship and Innovation Fund (RSIF).

References

[1] M. Agoundedemba, C. K. Kim, and H. G. Kim, “Energy Status in Africa: Challenges, Progress and Sustainable Pathways,” *Energies*, vol. 16, no. 23, 2023, doi: 10.3390/en16237708.

[2] L. González and M. Biencinto, “Modelling of Solar Thermal Electricity Plants in the POSYTYF Research Project for an Extensive Integra- tion of Renewable Energy Sources,” pp. 1–8, 2024, doi: https://doi.org/10.1016/j.jclepro.2022.134821.

[3] M. Agoundedemba, C. K. Kim, H.-G. Kim, R. Nyenge, and N. Musila, "Modelling and optimization of microgrid with combined genetic algorithm and model predictive control of PV/Wind/FC/battery energy systems," *Energy Reports*, vol. 13, pp. 238–255, 2025, doi: https://doi.org/10.1016/j.egyr.2024.12.008

[4] K. E. N’Tsoukpoe, K. Y. Azoumah, E. Ramde, A. K. Y. Fiagbe, P. Neveu, X. Py, M. Gaye, and A. Jourdane, “Integrated design and construction of a micro-central tower power plant,” *Energy for Sustainable Development*, vol. 31, pp. 1–13, 2016. doi: 10.1016/j.esd.2015.11.004

[5] Ministère des Mines et des Ressources Énergétiques, "Construction d’une centrale solaire de 50 MWc à Blitta," [Online].Available:https://energie.gouv.tg/projet/construction-dune-centrale-solaire-de-50-mwc-a-blitta/. [Accessed: Apr. 1, 2025].

[6] "Cinkassé elevation map," *Topographic-Map.com*. [Online]. Available: https://en-us.topographic-map.com/map-d1rvkl/Cinkass%C3%A9/. [Accessed: Apr. 1, 2025].

[7] Python Software Foundation, *Python 3.9.18*, [Online], Available: https://www.python.org/. [accessed: Jan.1, 2024].

[8] F. Moraga, M. T. Cerda, F. Dinter, and F. Fuentes, “Techno-Economic Analysis of the Integration of Large-Scale Hydrogen Production and a Hybrid CSP+PV Plant in Northern Chile,” *SolarPACES Conf. Proc.*, vol. 1, pp. 1–8, 2023, doi: 10.52825/solarpaces.v1i.669.

[9] A. Rouibah, D. Benazzouz, R. Kouider, A. Al-Kassir, J. García-Sanz-Calcedo, and K. Maghzili, “Solar tower power plants of molten salt external receivers in Algeria: Analysis of direct normal irradiation on performance,” *Appl. Sci.*, vol. 8, no. 8, 2018, doi: 10.3390/app8081221.

[10] C. Hernández, M. T. Cerda, C. Felbol, and F. Dinter, “Evaluation of the Levelized Cost of Energy With New Costs for Concentrating Solar Power Tower Plants in Northern Chile and Impact of Green Taxes,” *SolarPACES Conf. Proc.*, vol. 1, pp. 1–8, 2023, doi: 10.52825/solarpaces.v1i.615.

[11] M. Abbas, H. Aburideh, Z. Belgroun, Z. Tigrine, and N. Kasbadji Merzouk, “Comparative study of two configurations of solar tower power for electricity generation in Algeria,” *Energy Procedia*, vol. 62, pp. 337–345, 2014, doi: 10.1016/j.egypro.2014.12.395.

[12] A. L. Bukar, C. W. Tan, and K. Y. Lau, “Optimal sizing of an autonomous photovoltaic/wind/battery/diesel generator microgrid using grasshopper optimization algorithm,” *Sol. Energy*, vol. 188, no. March, pp. 685–696, 2019, doi: 10.1016/j.solener.2019.06.050.

[13] Z. Belboul, B. Toual, A. Kouzou, L. Mokrani, and A. Bensalem, “Multiobjective Optimization of a Hybrid PV / Wind / Battery / Diesel Generator System Integrated in Integrated in Microgrid: A Case Study in Djelfa, Algeria,” 2022, doi: https://doi.org/10.3390/en15103579.