

Thermodynamic Simulation and Efficiency Evaluation of Gas-Steam Combined Cycles Using Site-Specific Solar Irradiance Data from Kalburgi, India

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Abstract

The enactment of an integrated solar combined cycle with the combination of the solar power playing field with the combined cycle power plant cycles for the generation of electrical energy is considered to be more efficient. This is because the solar power field is integrated with the collective cycle power plant cycles. The optimal utilization of the thermal energy noted from the solar fields and from the warmness transfer fluid used to produce the steam is regarded as the most promising technique for modelling and simulating the thermodynamic model. This is because it utilizes the energy in the most efficient way possible. The power that the steam turbine cycle generates will therefore increase as a direct result of this action. The combined form of energy that is created by the ISSC systems that have been set up in Kalburgi in terms of their impact on energy consumption and overall efficiency has been evaluated. The statistics on sun irradiation that were obtained for seven distinct orientations served as the basis for the creation of the model that was suggested. The data on solar irradiance comes from the location under study, which is located in the Kalburgi district of Karnataka. The simulation results of the proposed method determine the performance of various parameters such as the variation in the solar irradiance, the effect of declination and sunrise hour angles on the energy absorption by the solar energy field, and the efficiency of the Rankine cycle and Brayton cycle.

Keywords: Integrated Solar Combined Cycle (ISCC), Solar irradiance, Thermal efficiency, Brayton-Rankine cycle, Simulation validation.

1. INTRODUCTION

According to the works of literature that are now accessible, renewable energies are the most significant kind of energy sources that are readily available in their natural state [95]. Solar energy, one of many forms of renewable energy, is widely used in the process of photovoltaic and concentrating solar power installations, which are used for the creation of electrical energy

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for residential use (CSP). That is largely due to the fact that solar irradiancies are available during daytime hours and can produce power in a manner that is highly effective. Furthermore, natural solar energy can be predicted in a quantity in climates which are hot and dry, like in the environment that predominate in Kalburgi being a normality. Factors that have to be accounted for when the design of a system for the conversion of solar energy is concerned are the level of solar radiation encompassed (solar radiation level) and the available data regarding the solar energy [1]. It is crucial to create thermodynamic models of the radiation intensity when the amount of solar irradiation is not available when needed due to decreasing solar irradiation availability. These models must be constructed as soon as possible. When there is insufficient irradiation from the sun available, one can use one of these models instead. In the vast majority of the studies that are currently accessible, researchers have shown that data on direct solar radiation is used for the purpose of identifying an appropriate thermodynamic simulation methodology [2].

Lauret, P [3] evaluate probabilistic solar irradiance forecasts across various climates using a benchmarking framework. They demonstrate that blending ground, satellite, and weather prediction data significantly improves intra-hour and intra-day forecast accuracy. The use of statistical post-processing methods enhances reliability, with skill scores notably higher for blended data. This study is vital for improving photovoltaic power integration. Di Laccio, J.L.[4] explored the use of smartphone light sensors for measuring solar irradiance. With calibration against satellite data, smartphones can produce reliable measurements, making them suitable for educational and research purposes. The approach provides a low-cost, accessible tool to support solar studies, especially in under-resourced areas and undergraduate teaching environments. Wang, Z[5] propose a dual-branch deep learning model that captures global and local temporal patterns for solar irradiance forecasting. Attention mechanisms and an autoregressive component enhance robustness. The model significantly outperforms traditional methods, showing over 40% improvement in accuracy, making it a valuable tool for operational solar energy forecasting. Anselmo, S[6] assesses the variability of solar radiation modeling outputs in urban GIS-based simulations. Using different input scenarios in GRASS GIS, results show a $\pm 20\%$ variation in estimates. The study underscores the need for empirical validation and provides insight for improving solar potential mapping in city planning and policy development. Beeharry, Y[7] presents hourly irradiance data from 12 sites across island regions, supporting energy forecasting and solar PV planning. The data, collected with precision instruments, is valuable

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for system performance analysis and decision-making. It fills a regional data gap and contributes to better understanding solar resource variability in tropical settings.

The performance of the hybrid ISSC system is strongly influenced by the simulation of the plant using actual meteorological data. This allows us to determine if such systems were capable of performing effectively in the particular conditions given at Kalburgi. Actual DNI (Direct Normal Irradiance) and DSR (Diffuse Solid Radiation) data from IMD (India Meteorological Department) are used by the researchers to assess solar field efficiency for various orientations [8]. All of the components of the power plant consist of a Rankine cycle, a Brayton cycle and a Heat Recovery Steam Generator and are interconnected[9]. Based on a number of stages, the thermodynamic modelling of the proposed ISSC is carried out. Each of this models are developed based on hourly and monthly radiation data from the Kalburgi district of Karnataka. In order to simulate the proposed ISSC described in this investigation, Brayton cycle models for gas turbines or Rankine cycle models for steam turbines are used for both. The Brayton cycle models include the compressor, combustion chamber and turbine. Preheater, superheater and steam turbine and condenser are included in the model of this Rankine cycle [10]. The simulation includes the ISSC system's interaction with the wide variety of radiation levels over a full calendar year. This study aims to check the efficiency and thermal enactment of the proposed ISSC model when it is installed in Kalburgi across all four seasons of the year. The performance will serve as the basis for this verification. The novelty lies in using site-specific Kalburgi irradiance data to simulate and evaluate ISSC systems using integrated Brayton and Rankine cycles [8-9].

2. METHODOLOGY

The Kalburgi sun irradiance measurements were used for experimental assessment. The average direct normal irradiance was measured at a latitude of 17.35 and longitude of 76.85 and the annual average was calculated as 5.28 kWh/m²/day. Similarly, the mediocre global parallel irradiance was measured with the same latitude and longitude and the annual average was calculated as 5.79 kWh/m²/day. When modelling the power plant, these factors are utilized as input (Table 1 and 2) [8].

Table 1 The power plant's parameters, as they pertain to the PTC

Parameters	Value
Characteristics of the collector	
Aperture width (m)	7.76
Aperture area (m ²)	545
Collector length (m)	99
Optical efficient (%)	0.8
Concentration ratio	82
Mirror reflectance	0.94
Receiver absorptivity	0.96
Receiver emittance	0.19
Characteristics of the solar field	
Alignment	North - South
Solar field area (m ²)	183.120
Number of collectors in each row	6
Number of lines	56
HTF inlet temperature (°C)	290
HTF outlet temperature (°C)	393

The radiation data are recorded on an hourly and monthly basis. Table 2 shows monthly average direct normal irradiance. Figure 1 shows the graphical view of average direct normal irradiance, and Figure 2 illustrates global horizontal irradiance.

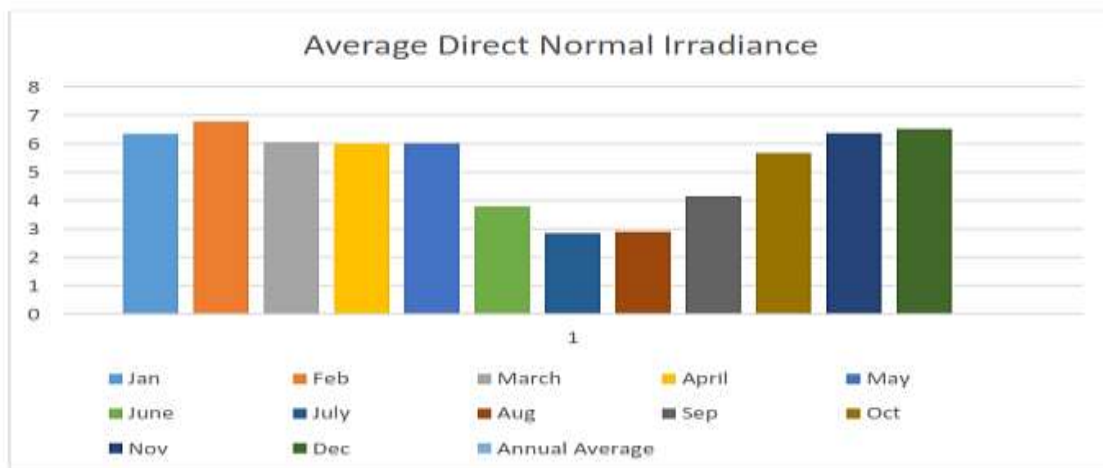


Figure 1 shows the Graphical view of Average Direct Normal Irradiance

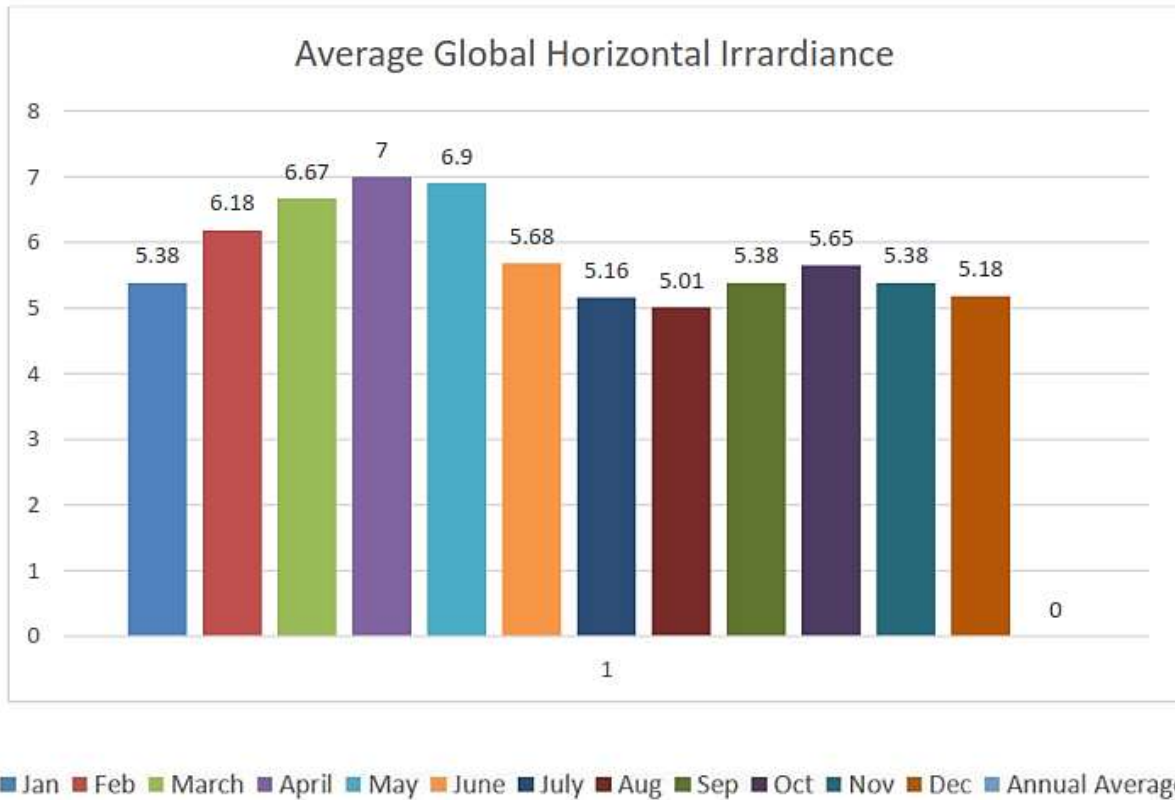


Figure 2 shows the Graphical view of average Global Horizontal Irradiance

Table 2 shows monthly average direct normal irradiance

Jan	6.35
Feb	6.78
March	6.05
April	6.01
May	6.02
June	3.79
July	2.84
Aug	2.90
Sep	4.14
Oct	5.67
Nov	6.37
Dec	6.52
Annual Average	5.28 kWh/m ² /day

The modelling of the sunshine field considers aspects including location, shape, or size of the solar field, optical performance, and time of irradiance availability. Radiation is measured at a specific latitude/longitude and time/day is tracked. Absorption and transfer coefficients of collectors are used to evaluate optical performance [8][11]. The Brayton cycle consists of the compressor, combustion chamber, turbine, economizer, evaporator, and super heater. The Rankine cycle considers evaporator (steam generator), preheater, and superheater. The mass flow rate, temperature, pressure, and isentropic efficiency are evaluated for both models. Simulink models were constructed using the Brayton and Rankine cycle layouts. Figure 3 depicts the gas turbine Brayton cycle model represents the Rankine cycle steam turbine model based on Kalburgi data.

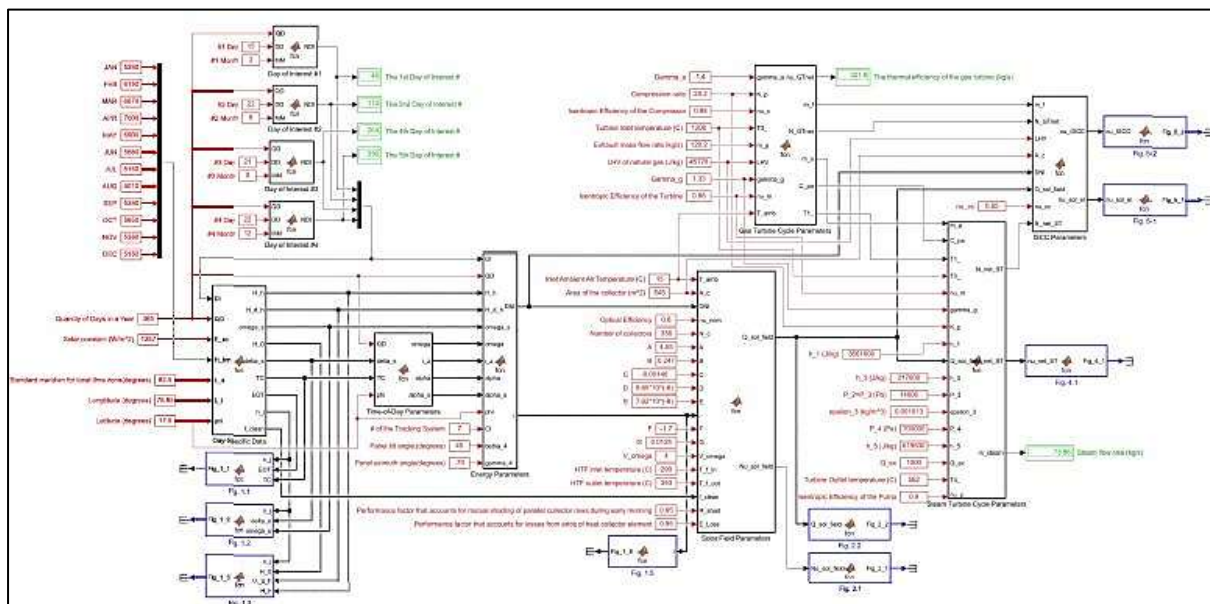


Figure 3 shows the Brayton cycle model implemented in Simulink for a gas turbine.

3. RESULTS AND DISCUSSIONS

The simulation model developed for this study facilitated a comprehensive thermodynamic analysis of an Integrated Solar Combined Cycle (ISCC) power system. In addition, this model took into account a region located at Kalburgi that was characterized by a hot and dry climate, as well as site specific solar irradiance data to account for the environmental conditions. This geographic location was crucial to the selection as the solar radiation availability and intensity is particularly important in the performance and efficiency of any power cycle based on solar radiation. The data collected were used to find that the average global horizontal irradiance (GHI) at the site is on average about 5,79 kWh/m²/day. Compared to the average DNI (5.28 kWh/m²/day), which is crucial for concentrating solar power technologies like parabolic trough

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collectors, the average values were 21.85 kWh/m²/day for tracked devices and 13.40 kWh/m²/day for untracked devices. Since these values provide a foundational input as to the potential and limits to solar energy integration within combined cycle systems at this location, they remain important. The simulation results showed the important trends in the system performance. As shown in **Figure 4**, the steam cycle exhibited a steady improvement in its thermal efficiency over time, suggesting effective utilization of solar input and recovery of thermal energy. Furthermore, **Figures 5 and 6** present graphical representations of the conversion efficiency from solar energy to electrical output and the overall thermal efficiency of the ISCC system, respectively. These figures clearly indicate that the integration of solar thermal energy into the combined cycle not only contributes to reducing fossil fuel dependency but also enhances system performance, particularly during peak irradiance hours. Such enhancements underscore the viability of ISCC systems in solar-rich regions like Kalburgi for achieving higher energy output and efficiency.

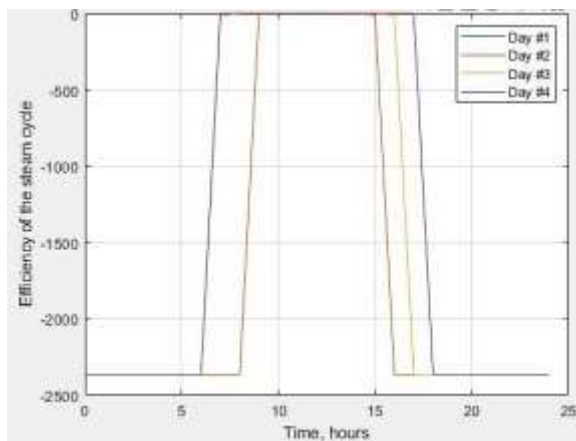


Figure 4 Efficiency of the steam cycle progression

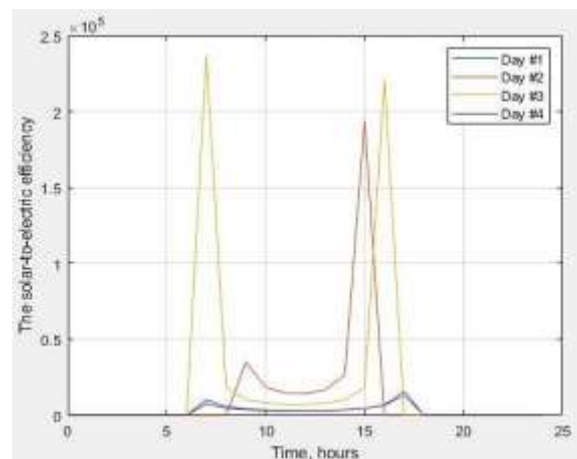


Figure 5 Efficiency of the ISSC solar to power conversion system

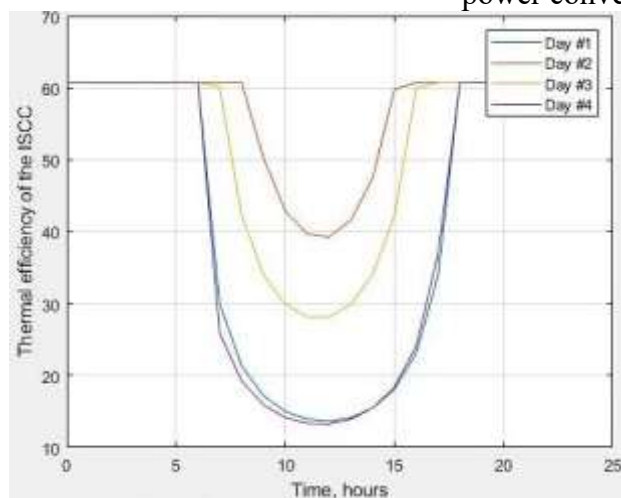


Figure 6 The power plant at ISSC maintains a high level of thermal efficiency.

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Figure 7 presents the Simulink model developed for the proposed Integrated Solar Combined Cycle (ISCC) power plant, utilizing site-specific solar irradiance data from Kalburgi. This model integrates the thermodynamic components—namely, the Brayton and Rankine cycles—along with the solar field, enabling a dynamic simulation of system behavior under actual environmental conditions. The inclusion of real-time radiation data enhances the accuracy of the performance predictions. **Figure 8** illustrates the average daily direct normal irradiation captured by the Rankine cycle over the course of a month. This plot highlights the temporal variation in solar energy availability, reflecting seasonal and diurnal patterns critical to optimizing thermal energy input. **Figures 9 and 10** display the changes in solar hour angle with respect to both time and angular declination parameters. These angles significantly affect the orientation and alignment of solar collectors and, consequently, the amount of solar radiation intercepted. As even small differences in the angle of incidence will yield lower energy capture, it is essential to accurately simulate these variations to maximize solar field efficiency. Data shown in these figures are crucial for the evaluation of the ISCC feasibility and the optimal energy output depending on the solar conditions.

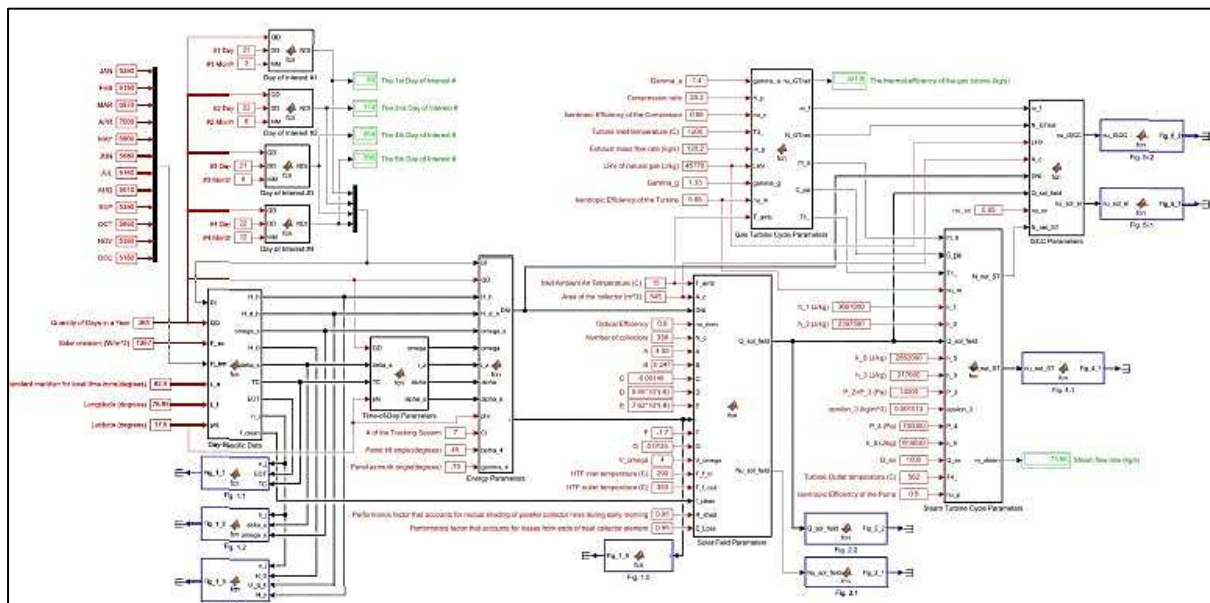


Figure 7 is a Simulink model depicting a Rankine cycle-based steam turbine model.

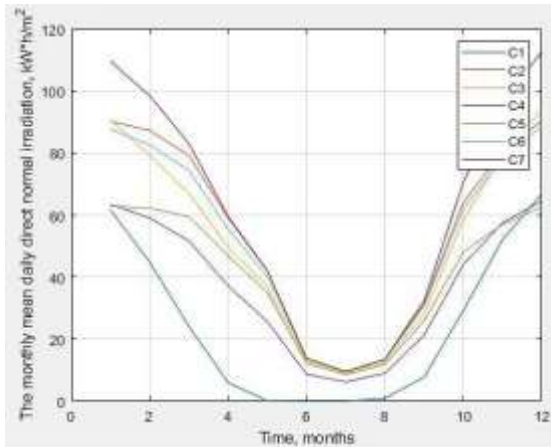


Figure 8 The Rankine cycle's mean day-to-day direct common irradiation over the sequence of a month.

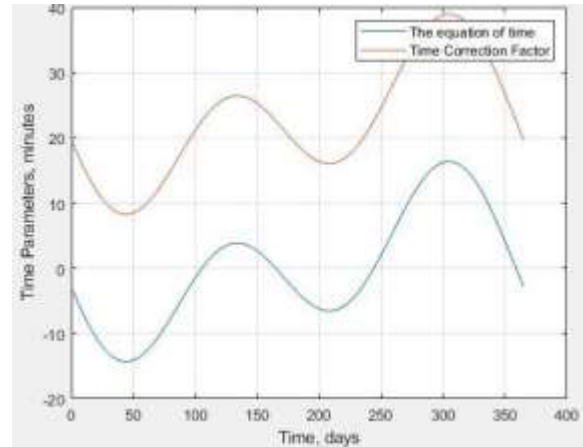


Figure 9 Declination and sunrise hour angles for Rankine cycle

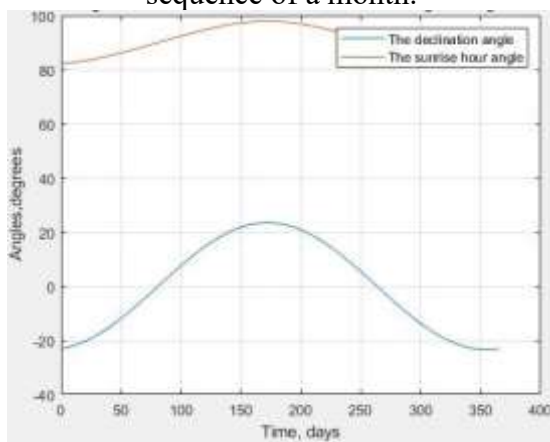


Figure 10 Declination and sunrise hour angles with respect to time and angles for

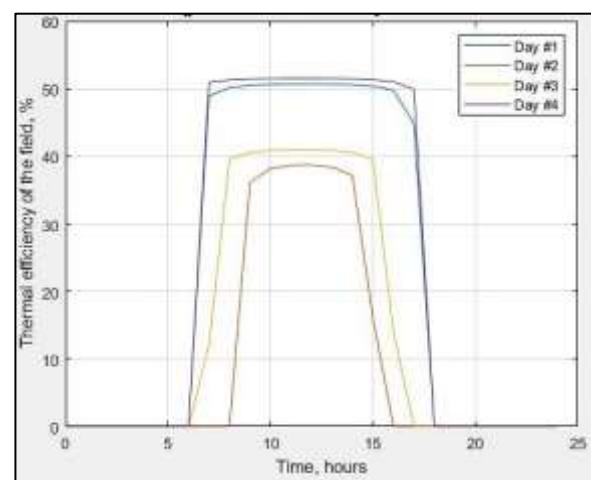


Figure 11 illustrates the thermal efficiency of the solar field with regard to the Rankine cycle.

Rankine cycle

As shown in Figure 11, the developed ISCC model is able to obtain high overall efficiency even under conditions with no major declination of the solar hour angle. This implies the system's robustness and adaptation under different solar geometric conditions. The model shows that the solar field can reach thermal efficiencies as high as 50 percent at mid day hours when the sun is at its zenith. The peak efficiency fits in with this point in time of maximum direct solar irradiance, perfect for maximum of storage and conversion of energy. Higher thermal efficiency correlates with increased amount of steam produced for the Rankine cycle, leading to increased power to be generated. It shows the model ability to take in solar energy without required complex solar tracking adjustments and still be efficient and potentially more cost effective. The ability to maintain high efficiency even under static solar positions emphasizes the suitability of the proposed configuration for regions with consistent high solar

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radiation, such as Kalburgi. This performance characteristic is crucial for enhancing the reliability and productivity of solar-augmented combined cycle power plants.

Figure 12 illustrates the solar field's contribution to the overall energy generation process in the proposed ISCC system. The simulation results reveal that the solar field is capable of producing a peak thermal output of up to 45 MW during the initial hours of strong solar irradiance, typically observed around midday. This period corresponds to maximum solar exposure, allowing the collectors to absorb and transfer a significant amount of heat to the working fluid. However, during early morning or late afternoon hours—and particularly under cloudy conditions—the thermal output can decline sharply, reaching a minimum of approximately 7 MW. This variation highlights the intermittent nature of solar energy and emphasizes the need for accurate modeling and possible integration of energy storage systems to stabilize output.

Figure 13 demonstrates the corresponding efficiency of the steam cycle when operated through a Rankine-based steam turbine. The simulation confirms that when sufficient thermal energy is supplied from the solar field, the Rankine cycle performs efficiently, converting the available heat into mechanical and subsequently electrical energy. These findings validate the integration of solar thermal input with traditional thermodynamic cycles, showcasing the system's capacity to adapt to fluctuating solar conditions while maintaining consistent performance and enhancing overall plant output.

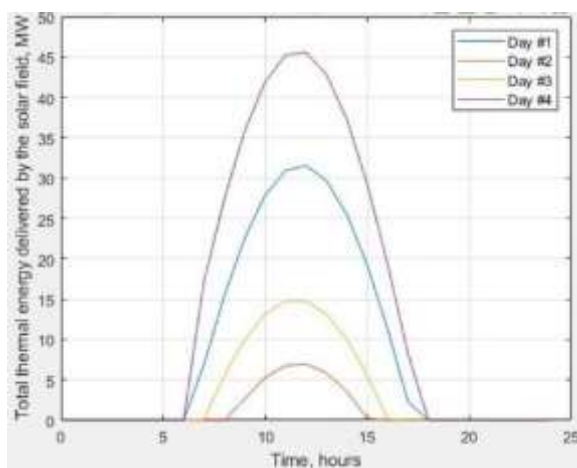


Figure 12 depicts the sun's contribution to the process.

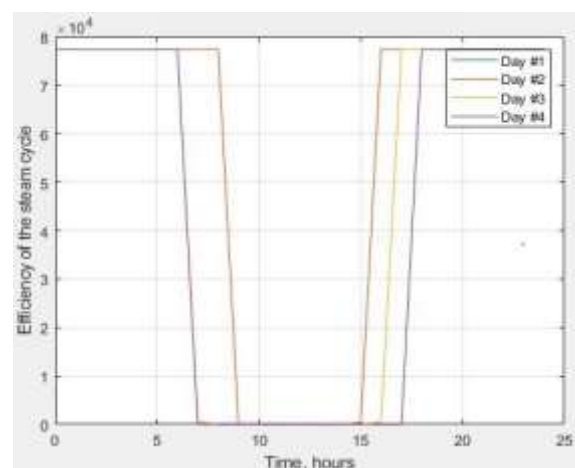


Figure 13 shows how effective the steam cycle can be when used to a steam turbine that operates on the principles of the Rankine cycle.

Figures 14 and 15 detail the system's behaviour as a function of time through two key stages, including solar-to-electric conversion efficiency, and the thermal efficiency of the heating

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system. Figure 14 shows the solar to electric efficiency of the system which indicates the percentage of the incident solar radiation that can be converted to electrical power. The graph indicates that the electrical output is improved by integrating solar because maximum solar irradiance occurs at mid day and then efficiency peaks. This is supported by fig 15, which displays the system's efficiency, the ratio of the thermal energy gained from the solar field and subsequent utilization on the steam generation cycle. The high heating efficiency indicates that the optimal heat transfer and minimum energy losses exist in the system[12-14].

A comparative validation between the experimental data and the simulated results obtained from both the existing ISCC model and the Kalburgi based model has been provided in figure 16. The considerable agreement of these results with the simulations indicates that the method of simulation used is accurate and reliable. This validation provides the robustness validation of the thermodynamic model and the possibility to use it in the real world. Further, Table 3 presents comparative analysis and quantitative results on the differences in the performance, further supporting the proposed model's improved efficiency and adaptability under the specified climatic condition of Kalburgi.

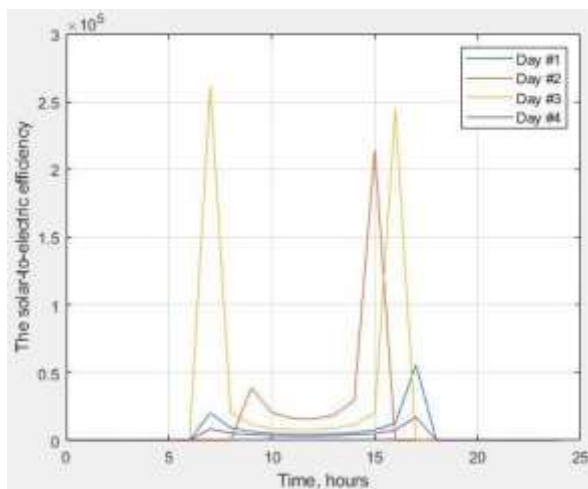


Figure 14 Solar Energy to electric efficiency of the ISCC

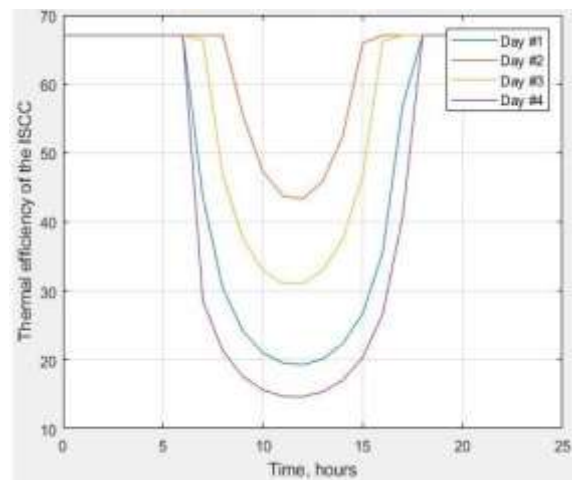


Figure 15 Efficiency of the ISCC's heating system in relation to the passage of time

The validation analysis shows a good correlation with available experimental data and thus it validates the reliability of the proposed model and that of the existing ISCC model. The degree of agreement between simulation and experiment confirms the accuracy of the simulation framework employed for evaluation of the thermodynamic performance of the integrated system. It is noteworthy that the ISCC model developed based on the solar irradiance data from Kalburgi site displays high improvement in the thermal and conversion efficiency over the previous models. In particular, the enhancements are apparent in the further use of energy in

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the peak solar conditions. Using real meteorological data from Kalburgi, the model is successfully implemented on local environmental dynamics that improve the energy output and system behavior estimation. However, localized customization at this level further helps with better system design and operational planning for regions sharing a similar climatic profile. Comparison further confirms the practical deployment of such hybrid systems in high radiation zones in achieving the proposed model to contribute significantly to the cleaning energy efforts at the same time as guaranteeing efficiency and reliability in utility scale power generation[15-16].

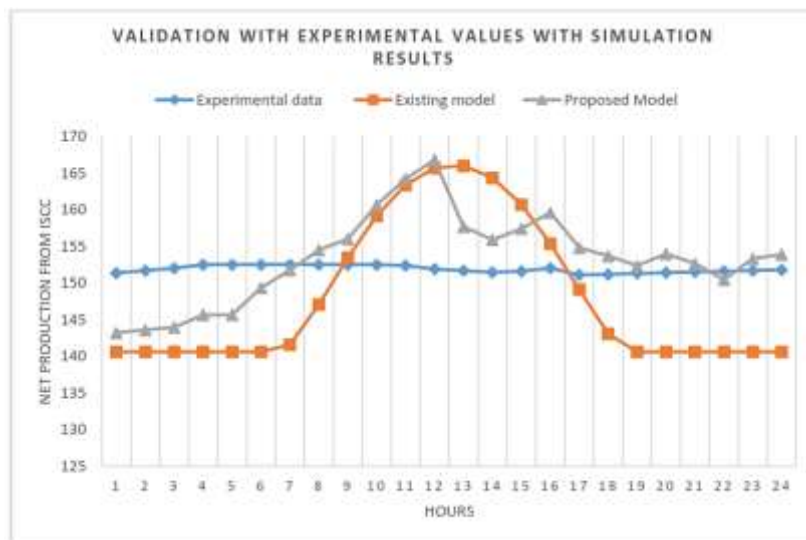


Figure 16 presents an illustration of the validation of experimental data with simulated outcomes of both the existing model and the proposed model.

Table 3: Comparison of the recommended model with the earlier studies and their respective analyses

Hours	Experimental data - Net Production from ISCC (MWh)	Existing model - Net Production from ISCC (MWh) [1]	Proposed Model - Net Production from ISCC (MWh)
1	151.361	140.6347	143.22
2	151.711	140.6347	143.59
3	152.033	140.6347	143.976
4	152.5	140.6347	145.687
5	152.5	140.6347	145.667
6	152.5	140.6347	149.35
7	152.5	141.5955	151.76
8	152.5	147.0784	154.5
9	152.5	153.4448	156
10	152.5	159.1656	160.65
11	152.4	163.38	164.21
12	151.9	165.68	166.80
13	151.69	165.99	157.70
14	151.46	164.33	155.90
15	151.61	160.70	157.40
16	152.02	155.39	159.60
17	151.1	149.11	154.80
18	151.19	143.09	153.70
19	151.32	140.63	152.35
20	151.41	140.63	153.98
21	151.5	140.63	152.66
22	151.62	140.63	150.46
23	151.71	140.63	153.33
24	151.79	140.63	153.89

4. CONCLUSIONS:

1. ISCC model site-specific solar irradiance data from Kalburgi reasonable simulation accuracy and a reliable system performance assessment under the real world climatic conditions is possible with solar irradiance data.
2. Thermal and solar to electric efficiency achieved by the hybrid Integrated Solar Combined Cycle (ISCC) system is high, hence showing its viability for energy production at these hot and dry climate.
3. This proposed thermodynamic model has the potential to join the Brayton and Rankine cycles in order to provide improved heat recovery or energy conversion and operation to changing solar conditions.
4. Validation against experimental data demonstrates the effectiveness and reliability of the Kalburgi-based ISCC model and shows superiority of such a model compared to others in terms of efficiency and prediction consistency.
5. Local modelling is emphasised since similar solar rich regions would also have the ability to utilise customised ISCC design to improve clean energy generation as well as to reduce dependency on fossil fuels.

REFERENCES

1. Derbal-Mokrane, H., Bouaichaoui, S., Gharbi, N.E., Belhamel, M., Benzaoui, A., 2012. Modelling and numerical simulation of an Integrated Solar Combined Cycle.
2. Zhu, G., Neises, T., Turchi, C., Bedilion, R., 2015. Thermodynamic evaluation of solar integration into a natural gas combined cycle power plant. *Renew. Energy* 74,815–824.
3. Lauret, P., Alonso-Suárez, R., Amaro e Silva, R., Boland, J., David, M., Herzberg, W., ... Zech, T. (2024). *The added value of combining solar irradiance data and forecasts: A probabilistic benchmarking exercise*. *Renewable Energy*.
4. Di Laccio, J. L., Monetta, A., Alonso-Suárez, R., Monteiro, M., & Marti, A. C. (2024). *Smartphone Light Sensors as an Innovative Tool for Solar Irradiance Measurements*. *Sensors*.
5. Wang, Z., Tang, Y., & Zhang, Z. (2024). *Dual-branch deep learning architecture for enhanced hourly global horizontal irradiance forecasting*. *Expert Systems with Applications*.
6. Anselmo, S., Safaeianpour, A., Moghadam, S. T., & Ferrara, M. (2024). *GIS-based solar radiation modelling for photovoltaic potential in cities: A sensitivity analysis for the evaluation of output variability range*. *Energy Reports*.
7. Beeharry, Y., Gokool, R., Ramgolam, Y. K., & Chiniah, A. (2024). *Global horizontal irradiance data for 12 stations in Mauritius, Rodrigues and Agaléga*. *Data in Brief*.

10.48047/jocaaa.2024.33.08.233

8. Manente, G., 2016. High performance integrated solar combined cycles with minimum modifications to the combined cycle power plant design. *Energy Convers.*
9. Rovira, A., Barbero, R., Montes, M.J., Abbas, R., Varela, F., 2016. Analysis and comparison of Integrated Solar Combined Cycles using parabolic troughs and linear Fresnel reflectors as concentrating systems. *Appl. Energy* 162, 990–1000.
10. Besarti, S.M., Padilla, R.V., Goswami, D.Y., Stefanik's, E., 2013. The potential of harnessing solar radiation in Iran: Generating solar maps and viability study of PV power plants. *Renew. Energy* 53, 193–199.
11. El Mghouchi, Y., El Bouardi, A., Choulli, Z., Ajzoul, T., 2014. New model to estimate and evaluate the solar radiation. *Int. J. Sustain. Built Environ.* 3, 225–234.
12. Zhan, H., Mahyuddin, N., Sulaiman, R., & Khayatian, F. (2023). Phase change material (PCM) integrations into buildings in hot climates with simulation access for energy performance and thermal comfort: A review. *Construction and Building Materials*, 397, Article 132312. <https://doi.org/10.1016/j.conbuildmat.2023.132312>
13. Miglioli, A., Aste, N., Del Pero, C., & Leonforte, F. (2023). Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods. *Energy and Built Environment*, 4(1), 39–56. <https://doi.org/10.1016/j.enbenv.2021.07.002>
14. Sajid Khan, M., Cui, J., Ni, Y., Yan, M., & Ali, M. (2023). Techno-economic and exergo-economic evaluation of a novel solar integrated waste-to-energy power plant. *Applied Thermal Engineering*, 223, Article 119929. <https://doi.org/10.1016/j.applthermaleng.2022.119929>
15. Tsai, C.-H., Li, F.-N., Liao, C.-Y., Su, Y.-Y., Tsai, K.-W., Hsiao, Y.-T., & Chang, Y.-M. (2023). Dimerized small-molecular acceptor enables the organic bulk-heterojunction layer with high thermal stability. *ACS Applied Materials and Interfaces*, 15(23), 27975–27983. <https://doi.org/10.1021/acsami.3c03073>
16. Vaibhav, S. D. V. R., Priyanshu, M., Subramani, S., Udupa, V., & Suma, M. N. (2023). Feasibility analysis of integrating thermo-electric generators to spacecraft solar panels. *Proceedings of the International Astronautical Congress, IAC*, 2023–October. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85187991159>