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Performance and Emission Assessment of Solar-Assisted Feed-Water Heating in Steam Power Plants

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ABSTRACT

Recently, about 95% of Libya's electricity is generated from fossil fuel–fired power plants. In recent years, the average efficiency of these thermal plants has shown a negative trend, underscoring the need for investment and research to enhance their performance. This paper examines the potential of integrating solar thermal energy to reheat the parallel feed-water at the Khums steam power plant, with the aim of improving overall efficiency and reducing dependence on conventional fuels. A simulation model was developed using Aspen HYSYS and SAM software to analyze the system's performance before and after solar integration. The results showed increased efficiency of solar-assisted plant achieved an overall efficiency of 42.6%, compared to 33.0% for the conventional system reduced fuel consumption and emissions, along with promising economic feasibility for the proposed system.

Keywords: Solar thermal integration, Feedwater preheating, Steam power plant.

تقييم الأداء والانبعاثات لتسخين مياه التغذية بمساعدة الطاقة الشمسية في محطات توليد الطاقة البخارية

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ملخـــــــص البحــــــــث

في الآونة الأخيرة، يُولَّد حوالي 95% من كهرباء ليبيا من محطات توليد الطاقة التي تعمل بالوقود الأحفوري. أظهر متوسط كفاءة هذه المحطات الحرارية اتجاهًا سلبيًا، مما يُؤكد الحاجة إلى الاستثمار والبحث لتحسين أدائها. تبحث هذه الورقة البحثية في إمكانية دمج الطاقة الشمسية الحرارية لإعادة تسخين مياه التغذية الموازية في محطة توليد الطاقة البخارية بالخمس، بهدف تحسين الكفاءة الكلية وتقليل الاعتماد على الوقود التقليدي. طُوِّر نموذج محاكاة باستخدام برنامجي Aspen HYSYS وSAM لتحليل أداء النظام قبل وبعد دمج الطاقة الشمسية. أظهرت النتائج زيادة في كفاءة المحطة المدعومة بالطاقة الشمسية، حيث حققت كفاءة إجمالية بلغت 42.6%، مقارنةً بنسبة 33.0% للنظام التقليدي، مما أدى إلى انخفاض استهلاك الوقود والانبعاثات، إلى جانب جدوى اقتصادية واعدة للنظام المقترح.

الكلمات المفتاحية: دمج الطاقة الشمسية الحرارية، التسخين المسبق لمياه التغذية، محطة توليد الطاقة البخارية.

1. INTRODUCTION

Most countries rely on oil to meet their energy generation needs, which places a significant burden on national economies. In addition, the combustion of heavy oil releases greenhouse gases with severe negative impacts on the environment. Therefore, an alternative clean heat source is required to help conventional power plants reduce fuel consumption and, consequently, emissions. Solar energy is a clean and abundant resource, with the Earth receiving an estimated 630,000 TWh annually. However, the large-scale commercialization of solar power plants remains limited due to high investment costs and relatively low efficiencies. A promising approach is the integration of solar thermal energy with existing power stations. Coupling solar thermal systems with traditional steam Rankine cycle plants provides an effective means of utilizing solar energy for power generation while simultaneously reducing oil consumption and mitigating environmental pollution [1].

Preheating is another method proposed to improve the overall efficiency of power generation cycles. Preheating is applicable in Rankin cycles with steam turbines (STs) improving the overall thermal efficiency and cycle output. For example, in regenerative Rankine cycles, steam extracted from the turbine is used to preheat boiler feed water, which leads to increasing the efficiency of the station. A large portion of traditional energy is consumed in the power station sector. Although this requirement cannot be reduced to zero, it can be reduced by using solar energy. Energy conservation is a major goal of the economy and will continue in the near future. To protect the environment from pollution caused by burning fossil fuels, solar energy is becoming more popular as the largest source of carbon-free renewable energy [2].

An improvement in efficiency or reduction in fuel consumption can be achieved by taking advantage of preheating in different thermal cycles used to generate power. Steam preheating in Rankin cycles can effectively improve the performance of plants. The thermal energy content of the sun is applicable for preheating in an environmentally friendly way, which can be applied in other systems such as fuel cells, In addition. For solar-assisted preheating, appropriate media such as collectors must be used to concentrate the solar radiation to obtain a higher energy density [3,4].

2. STATE OF THE ART REVIEW

The Khoums power plant is one of the main power plants in Libya, and it works on the principle of the steam cycle to generate electricity through the combustion of fuel. The station consists of several generating units, the second unit was chosen as the field for this study.

The second unit in the Al-Khums power station is a steam unit that operates with a capacity of 100 MW and relies on the combustion of heavy fuel (mazut) or natural gas to generate the steam needed to operate the turbines. The feed water in the boiler is heated to produce steam of high pressure and temperature, which drives a steam turbine connected to an electric generator, thus producing electricity.

2.1 Current Steam Power Plant Process

The feed-water enters at a mass flow rate of 270 t/h and a temperature of 40 °C .It is first heated in the feed-water heater (FWH) by bleed steam extracted from the boiler drum, raising its temperature to 140 °C at 3.62 bar .The preheated water is then pumped up to 130 bar before entering the boiler. The boiler produces high-pressure steam at 570 °C, which is sent to the high-pressure (H.P.) turbine. The H.P. turbine exhausts steam at 22 bar and 312 °C; this steam is reheated to 560 °C using bleed steam and then sent to the intermediate-pressure (I.P.) turbine. The I.P. turbine exhausts steam at 5 bar and 337 °C to the low-pressure (L.P.) turbine. The L.P. turbine exhaust is condensed in the condenser from 125°Cat atmospheric pressure down to 40 °C—and the condensate is returned as feed water for the next cycle. The steam turbines deliver 100 MW of power with an overall thermal efficiency of 33%. Fuel and air consumption rates are 24.2628 t/h and 397.327 t/h, respectively. Split the feed-water stream into two 70% follows the conventional heating path through in boiler 30% to the solar system for preheating. After solar heating, recombine the streams and send them together to the boiler. By preheating part of the feed-water with solar energy, the required fuel input and overall heat input (Qin) are reduced, boosting cycle efficiency and cutting CO_2 emissions [5,6].

Steam power plant diagram without solar energy system is shown in figure 1a and Schematic of the solar-aided power plant with storage unit in figur 1b.

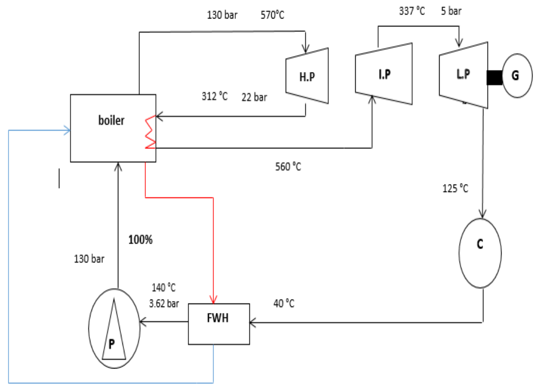

Fig 1a. Steam power plant without solar energy system.

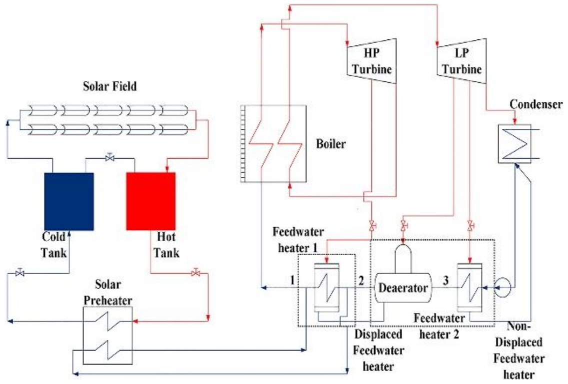

Fig 1b. Schematic of the solar-aided power plant with storage unit.

2.2 Parabolic Trough Solar Collector.

A parabolic trough solar collector (PTC) is a type of solar thermal system that uses a parabolic-shaped reflector to focus sunlight onto a receiver tube. The working fluid inside the tube absorbs heat and transfers it for useful applications such as power generation, heating process. It is shown in figure 2.

A parabolic trough solar collector system is used to generate steam for the steam power plant. To provide the required steam for power plant, parabolic trough solar collector system with the climatic conditions of the Al-Khoums power station located in the city of Al-Khums Libya with the latitude of Al Khums, Libya is 32.64861000, and the longitude is 14.26191000. Since solar energy is not always available, the hot dissolved salts are stored during the day when solar energy is available and are used 24 hours a day [5].

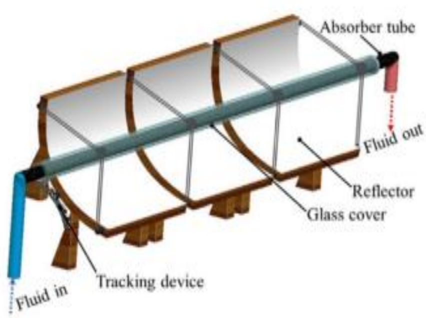

Fig 2. Schematic of the solar parabolic trough collector.

3. MATERIAL AND METHODS

3.1 The Aspen Hysys model of steam power plant

The steam Power Plant process modeling by aspen hysys version v.11. in the flowing steps:

1- Input in the Aspen properties list are all components of liquid fuel, gas flue and steam in Table 1 and components of molten salt in Table 2.

2- Input in Aspen properties list fluid package is Peng-Robinson this package is used for gas and steam power plant and fluid package NRTL for molten salt in solar energy system.

3- Input in Aspen simulation environment, all streams (feed product and connection streams between equipment) with specification of streams and equipment (pumps, heat exchangers, boiler (fire heater) and turbine) with specification and operations conditions it used in process modeling.

Table 1. The components for liquid fuel, gas flue and steam in Aspen Hysys.

Compone	Type	Compone	Type
H2O	Pure	n-C17	Pure
Nitrogen	Pure	n-C18	Pure
Oxygen	Pure	n-C19	Pure
CO2	Pure	n-C20	Pure
CO	Pure	n-C21	Pure
n-Octane	Pure	n-C22	Pure
n-Nonane	Pure	n-C23	Pure
n-Decane	Pure	n-C24	Pure
n-C11	Pure	n-C25	Pure
n-C12	Pure	n-C26	Pure
n-C13	Pure	n-C27	Pure
n-C14	Pure	n-C28	Pure
n-C15	Pure	n-C29	Pure
n-C16	Pure	n-C30	Pure

Table 2. The components for molten salt in Aspen Hysys.

Component	Type
Sodium-Nitrate	Pure Component
Potassium-Nitrate	Pure Component
Water	Pure Component
Calcium-Nitrate	Pure Component

3.2 Process description

Steam power plant process flow diagram in Fig 3. The water feed mass flow rate is 270 Ton/h at 40 ºC is pumped by P-101 to 3.62 bar and heated by steam exhaust from boiler in heat exchanger E-101 to 140 ºC then separation vaper by water tank and pumped by P-102 to 130 bar. The high-pressure water is split to 30% by mass to be sent to the solar system to be heated to 500 ºC and the rest is heated to 570. Following the heating process, both streams are recombined and supplied to the high-pressure steam turbine (ST-101). The exhaust steam from ST-101 exits at 22 bar and 312 °C, after which it undergoes reheating to 560 °C utilizing the boiler exhaust gases before entering the medium-pressure steam turbine (ST-102). The outlet conditions of ST-102 are 337 °C and 5 bar, and the steam is subsequently expanded through the low-pressure steam turbine (ST-103).

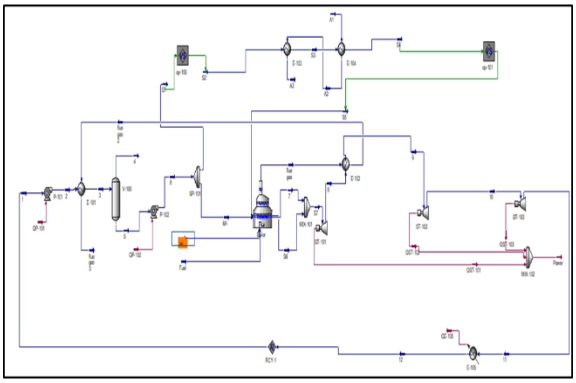

Fig 3. Steam power plant with solar energy system.

The exhaust from ST-103, characterized by a temperature of 125 °C at atmospheric pressure, is cooled in the heat exchanger E-105 to 40 °C, enabling condensation and recycling of the working fluid back into the cycle.

Under solar-assisted operation, the integrated system produces 100.9 MW of electrical power, achieving an overall thermal efficiency of 42.6%. In this configuration, the required fuel and air inputs are 18.75253 ton/h and 307.09 ton/h, respectively. In contrast, the baseline configuration without solar integration necessitates 24.2628 ton/h of fuel and 397.327

ton/h of air to generate 100.08 MW at an efficiency of 33%.

The incorporation of solar thermal energy therefore results in a net reduction of 5.51 ton/h in fuel consumption, representing a substantial improvement in both energy efficiency and operational sustainability.

In thermodynamic analysis, the absolute enthalpy of a stream—whether positive or negative—has no physical meaning, as it depends entirely on the chosen reference state. What is physically relevant is the change in enthalpy (ΔH) between two states, which remains the same regardless of the reference point and directly represents the energy transfer in the system [6].

3.3The SAM software for modeling the performance of renewable energy projects

The System Advisor Model (SAM) is a software tool developed by NREL (National Renewable Energy Laboratory) for modeling the performance and financial feasibility of renewable energy projects, including parabolic trough solar collectors.

The latest version is SAM 2023.12.17, includes updates and new features to enhance simulation accuracy for solar power plants, wind energy, battery storage, and other renewable technologies.

Key Features of SAM for Parabolic Trough Solar Collectors:
1. Performance Modeling
Simulates energy output based on solar irradiance, weather data, and system configuration.
Accounts for optical efficiency, thermal losses, and fluid flow properties.
2. Economic Analysis
Calculates Levelized Cost of Energy (LCOE).
Compares project financing options (PPA, feed-in tariffs, etc.).
3. Thermal Storage Integration
Models heat transfer fluid (HTF) behavior in a parabolic trough system.
Simulates thermal energy storage (TES) for dispatchable power generation.

4. Weather Data Integration
Uses real-world weather files (TMY, TMY2, TMY3) for accurate solar resource assessment.
5.Detailed Loss Calculations
Accounts for mirror soiling, tracking errors, and thermal losses in the receiver tube [7].
A parabolic trough solar collector system is used to generate steam for the power plant. Solar energy is not always available, the hot dissolved salts are stored during the day when solar energy is available and are used 24 hours a day.
A parabolic trough solar collector system modeling by using SAM software (SAM.2023.12.17). The System Advisor Model (SAM) is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry and SAM makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that you specify as inputs to the model. This software is a powerful tool for simulation of the complex model for Photovoltaic system and provides highly accurate results. Achieving real and accurate results from simulation is possible by choosing the correct location and type of parabolic trough solar collector system.

The parabolic trough solar collector system is designed to operate efficiently by collecting and storing thermal energy to ensure continuous steam production over a 24-hour period. During the 8-hour solar radiation period, the collector absorbs sunlight and transfers heat to a working fluid, which is then used to generate steam. However, since steam is required throughout the day, a portion of the collected thermal energy is immediately used for steam production, while the remaining energy is stored in a thermal energy storage (TES) system for later use. This stored heat is then utilized during the 16-hour non-sunlight period, ensuring a stable and continuous steam supply even when solar radiation is unavailable [8,9].

3.4 Power Plant with Solar Energy of H–S diagram

The H–S diagram in figure 4 illustrates the thermodynamic behavior of the solar-assisted steam power plant by plotting molar enthalpy against molar entropy for various process states. The curve shows several sharp peaks and troughs, indicating different stages of the steam cycle such as heating, expansion, condensation, and pumping. Notably, the high entropy peaks, reaching values above 400 kJ/kgmol·°C, likely correspond to points where solar energy from the molten salt system contributes additional heat to the water, resulting in high-temperature, high-pressure steam entering the turbine. Conversely, the sharp drops in entropy represent processes where energy is extracted from the steam, such as during turbine expansion and condensation. These transitions highlight the effective utilization of solar heat to elevate the system's energy content before expansion. However, some negative entropy values appear in the data, which are physically unrealistic and may be attributed to inconsistencies in unit settings, reference states, or data extraction errors from the simulation. Despite these anomalies, the overall shape of the curve reflects a modified Rankin cycle, showing how solar integration enhances entropy at key points, contributing to improved cycle efficiency and reduced fossil fuel consumption. This diagram effectively supports the thermodynamic analysis by visually demonstrating the impact of solar energy on the power plant's performance.

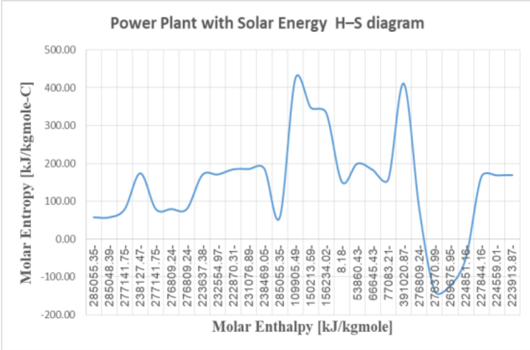

Fig 4. The H–S diagram of Power Plant with Solar Energy**.**

3.5 Power Plant without Solar Energy of H–S diagram

The H–S diagram in figure 5 titled "Power Plant without Solar Energy – H vs S" presents the thermodynamic behavior of the conventional steam power plant by plotting molar enthalpy against molar entropy across different process states. The curve reflects the stages of the Rankine cycle namely, feedwater heating, evaporation, expansion through the turbine, and condensation. The plot shows a relatively smoother progression compared to the solar-assisted version, with entropy peaking at around 400 kJ/kgmol•°C, corresponding to the high-pressure, high-temperature steam generated by fossil fuel combustion in the boiler. This peak is followed by a sharp drop, indicative of expansion in the turbine, where steam does mechanical work and loses energy and entropy. Subsequent values remain relatively stable, suggesting efficient condensation and pumping processes in the cycle. This chart reinforces the conclusion that solar energy enhances the cycle's thermodynamic behavior and efficiency, offering greater sustainability and fuel economy.

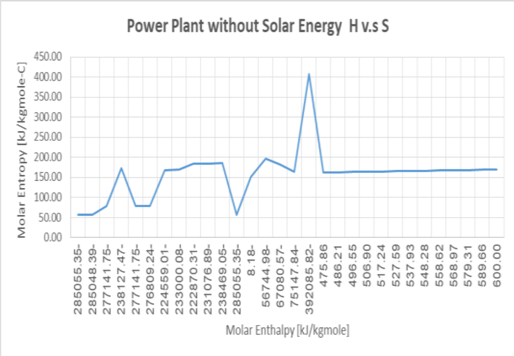

Fig 5. The H–S diagram of Power Plant with Solar Energy**.**

3.6 The comparison between the two H–S diagrams

The comparison between the two H–S diagrams one for a power plant with solar energy and the other without highlights several key thermodynamic differences resulting from the integration of solar power. In the solar-assisted cycle, the diagram exhibits more pronounced fluctuations in entropy, with multiple peaks exceeding 400 kJ/kgmol·°C. These variations reflect the additional thermal energy supplied by the solar collector system, which boosts the steam's temperature and entropy at various stages of the cycle. In contrast, the conventional power plant without solar input shows a smoother, more stable H–S curve, with only one major entropy peak and fewer fluctuations. This indicates a more controlled and uniform energy input from fossil fuels, as expected in a traditional Rankin cycle. Additionally, the enthalpy values in the solar-powered system cover a wider and more variable range, including some extremely negative values that may stem from simulation reference settings or data inconsistencies. On the other hand, the enthalpy data in the non-solar system is more consistent and physically realistic. The irregular shape of the solar-powered curve suggests dynamic thermal behavior due to variable solar input, whereas the standard cycle maintains a predictable pattern. Overall, the solar-assisted power plant demonstrates the potential for higher thermodynamic performance and efficiency, albeit with added complexity in modeling and data interpretation.

3.7 Powr calculation

A comparison of power requirements and overall performance of the steam power plant, with and without solar thermal integration, is summarized in Table 3.

Table 3. comparison of power requirements and overall performance of the steam power plant.

Category	Parameter	without Solar Integration	with Solar Integration
Pump Power Requirements	Pump P-101 (MW)	0.03	0.03
	Pump P-102 (MW)	1.38	1.38
	Total Pump Power (MW)	**1.41**	**1.41**
Fuel Heat Input (LHV Basis)	Fuel LHV (kJ/kg)	44,357.27	44,357.26
	Fuel mass flow rate (kg/s)	6.7397	5.2090
	Heat added (MW)	298.95	231.06
	Total Heat Input (MW)	**298.95**	**231.06**
Turbine Power Output	ST-101 (MW)	35.14	35.97
	ST-102 (MW)	34.17	33.17
	ST-103 (MW)	30.77	30.77
	Total Turbine Power Output (MW)	**100.08**	**99.91**
Performance	Net Power Output (MW)	98.67	98.50
	Overall Efficiency (%)	33.0%	42.6%

4. RESULTS AND DISCUSION

The Aspen HYSYS simulation results:
The simulation results obtained from Aspen HYSYS, comparing the power output and overall efficiency of the steam power plant with and without solar thermal integration, are summarized in Table 4.

Table 4. Comparison of Power Output and Efficiency with and without Solar Integration.

Parameter	with Solar Integration	without Solar Integration
Total Power Output (MW)	99.91	100.08
Net Power Output (MW)	98.50	98.67
Overall Efficiency (%)	42.6%	33.0%

Figure 6 illustrates the **overall thermal efficiency** of the steam power plant with and without solar thermal integration. The graph clearly shows the improvement from **33.0%** in the conventional configuration to **42.6%** with solar assistance, representing a relative increase of approximately 29%.

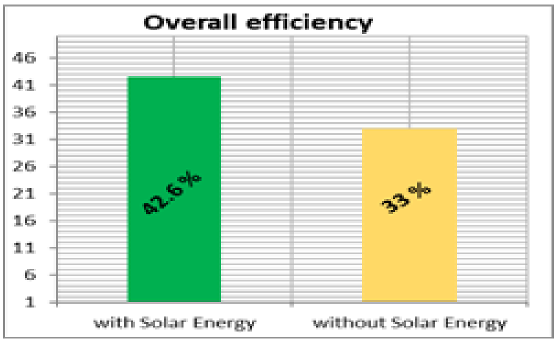

Fig 6. Overall efficiency graph**.**

Figure 7 illustrates the **net power output** for both cases. Despite the significant reduction in fuel consumption with solar integration, the net electrical output remains nearly constant at approximately **98.6 MW**, demonstrating the effectiveness of solar thermal augmentation in maintaining power generation while reducing fuel usage and emissions.

While the gross power output is very similar in both configurations, the solar-assisted system is more efficient by nearly 10%, which is significant. This is because part of the energy input comes from solar heat, which reduces fuel dependency. Fuel consumption and air requirement are summarized in Table 5.

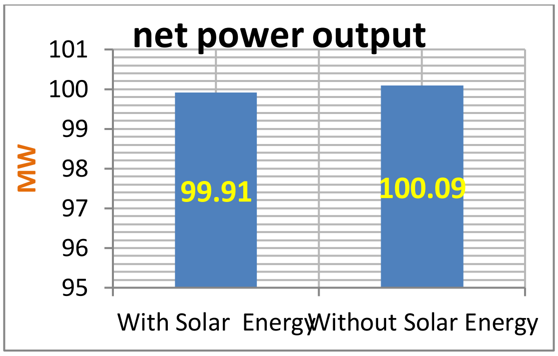

Fig 7. Net power output graph.

Table 5. Fuel and Air Consumption with and without Solar Integration.

Parameter	With Solar Integration	Without Solar Integration
Fuel Consumption (ton/h)	18.75	24.26
Air Requirement (ton/h)	307.09	397.33

The solar integration saved about 5.5 ton/h of fuel and approximately 90 ton/h of air. This is a direct benefit in terms of fuel cost savings and reduced environmental emissions. The figures [8,9] demonstrate the fuel and air consumption for both cases.

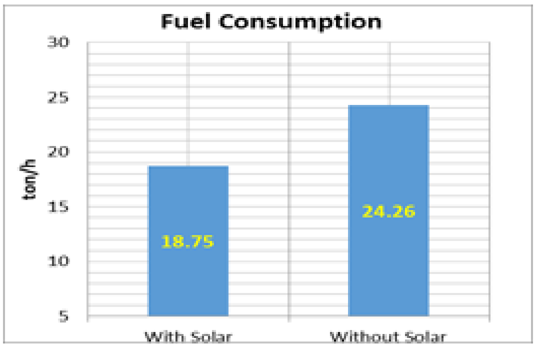

Fig 8. Fuel Consumption graph.

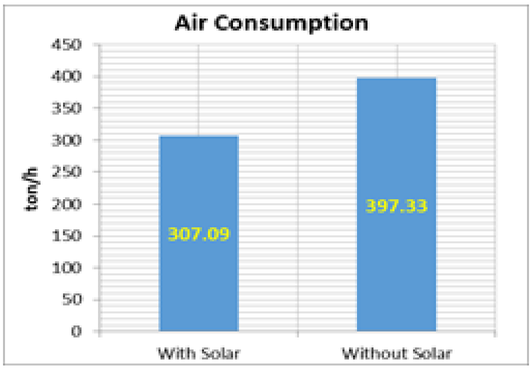

Fig 9. Air Consumption graph**.**

Solar Heating Contribution In the solar-integrated cycle:

1. 30% of the high-pressure water is pre-heated using molten salt from the solar energy system before entering the boiler.
2. The water reaches up to 570 °C before entering the high-pressure turbine, compared to conventional heating which also reaches this temperature but requires more fuel.

The solar thermal subsystem reduces the thermal load on the boiler, thereby lowering the consumption of fossil fuels. This highlights the effectiveness of a hybrid design, in which solar energy acts as a partial substitute for combustion-based heat input. The resulting impact on CO_2 emissions, for both configurations with and without solar energy integration, is summarized in Table 6 and demonstrated in figure 10. The emission CO2 were calculated using the following equation:

*Emissions CO2 kg/h = fuel Emission kg/h * Emission Factor*

Emission Factor = 3.114 kg per 1kg of heavy fuel

Table 6. Fuel Consumption and CO_2 Emissions with and Without Solar Integration.

Parameter	**With Solar Integration**	**Without Solar Integration**	**Reduction**	**Reduction (%)**
Fuel Consumption (kg/h)	18750	24260	5510	—
Fuel Consumption (ton/h)	18.75	24.26	5.51	**22.7%**
CO_2 Emissions (kg/h)	58387.5	75545.64	17158.14	—
CO_2 Emissions (ton/h)	58.40	75.55	**17.15**	**22.7%**

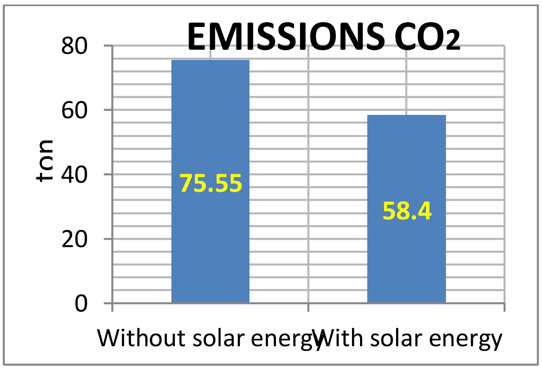

Fig 10. emission of CO2 graph.

5. CONCLUSION

This study successfully modeled and evaluated the performance of a steam power plant using Aspen HYSYS, comparing two configurations: one powered solely by fossil fuels and the other supported by a solar thermal energy system using molten salt.

The results demonstrate that integrating solar energy into the steam cycle significantly improves the plant's thermal efficiency and reduces fuel consumption:

1. The solar-assisted steam power plant achieved an overall thermal efficiency of 42.6%, compared to 33.0% for the conventional system, representing a relative increase of approximately 29%.

2. Fuel consumption decreased from 24.26 ton/h to 18.75 ton/h, saving about 5.5 ton/h, along with a proportional reduction in air demand.

3. CO_2 emissions were reduced from 75.55 ton/h to 58.40 ton/h, a decrease of 17.15 ton/h, corresponding to a 22.7% reduction.

4. Despite nearly identical net power outputs (~98.6 MW), the hybrid system achieved this with a significantly lower fossil fuel input, demonstrating the effectiveness of solar thermal augmentation.

5. Detailed material and energy balances confirmed conservation of mass and energy, and all unit operations were thermodynamically consistent.

6. The solar thermal system was independently designed using SAM software to estimate achievable thermal output, which was then integrated into the steam power plant model to enhance its thermal input and overall performance.

RECOMENDATION

Based on the analysis and results of the hybrid steam power plant, several recommendations can be made to enhance the system's performance and sustainability. Firstly, it is advisable to increase the level of solar energy integration beyond the current 30% of the high-pressure water stream, as this could further improve thermal efficiency and reduce fuel consumption. To maximize heat transfer between the molten salt and water, the heat exchanger network particularly E-103 and E-104 should be optimized through design improvements such as counter-current flow arrangements and enhanced heat transfer surfaces.

The implementation of a real-time monitoring and control system is also recommended to ensure stable and efficient operation, particularly within the solar heating loop where fluctuations in solar intensity can affect performance. Additionally, a detailed economic evaluation should be conducted to assess the long-term financial benefits of solar integration, factoring in fuel cost savings and the potential for earning carbon credits.

From an environmental standpoint, it is important to quantify the reduction in greenhouse gas emissions due to lower fossil fuel use, which would support the case for adopting cleaner energy solutions. Moreover, the incorporation of thermal energy storage using molten salt is suggested to maintain plant operation during periods of low or no sunlight, thereby improving system reliability and flexibility [10]. Finally, future studies could explore the integration of other renewable energy sources, such as biomass or geothermal energy, to create a more diversified and resilient hybrid energy system. These measures collectively contribute to advancing the efficiency, economic viability, and environmental sustainability of steam power generation.

It is recommended in the future to conduct a comprehensive economic study that takes into account the cost of the solar thermal system alongside the savings resulting from the reduced fuel consumption in the steam power plant, in order to determine the feasibility of investing in this type of integration."

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