

Simulation of solar-coal hybrid power plant based on the Rankine cycle

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Abstract: The use of solar energy to generate electricity in Power Plant (PP) based on the Rankine cycle is currently a strongly developed CSP system (Concentrating Solar Power) technology. Combining CSP systems with an existing Rankine cycle in coal-fired Power Plant (PP) or Combined Heat and Power Plant (CHP) can increase the maximum output of a power plant and effectively provide a transition for fossil fuel-based technologies to the use of renewable energy sources such as hybrid or renewable energy-only systems. The paper presents simulation results of a steam Rankine cycle with solar power plant components. The hybrid power system makes it possible to reduce the use of coal fuel and provide high efficiency and output power. The calculations were carried out using Epsilon Professional software.

Keywords: RENEWABLE ENERGY SOURCES, HYBRID ENERGY SYSTEM, THERMODYNAMIC MODELING, ENERGY TECHNOLOGIES

1. Introduction

Coal continues to play a vital role in the energy mix of many countries, particularly in the developing countries, where power generation infrastructure is still largely dependent on this resource [1-3]. However, the environmental challenges posed by fossil fuel-based electricity production - most notably the emission of greenhouse gases - have become a pressing global issue, contributing significantly to climate change and global warming. These concerns underscore the urgent need to modernize existing coal-fired power plants and accelerate the integration of cleaner, renewable energy sources into national energy systems.

Concentrated Solar Power (CSP) systems and Thermal Energy Storage (TES) offer a promising solution for reliable power generation under varying solar radiation conditions. This advantage positions CSP above other renewable technologies, such as photovoltaics and wind power, which are often regarded as leading alternatives to fossil fuels. Concentrated Solar Power (CSP) technology has gained prominence for its potential to provide a sustainable, efficient, and diverse energy mix, making it an essential component of future energy systems [4]. CSP systems face significant challenges, including high initial investment costs, lower efficiency compared to fossil fuel-based systems, and the technical complexities associated with large-scale TES implementation. Integrating solar energy into coal-fired power plants forming a Solar-Coal Hybrid Power Plant (SCHPP), presents a viable approach to address these issues. This hybrid system has substantial potential to reduce coal consumption while mitigating the limitations associated with standalone CSP plants [5].

2. Analyzed energy systems

2.1. Steam power plant

The analyzed steam power plant is a power unit consisting mainly of a steam boiler, high-pressure steam turbine, low-pressure steam turbine, generator, condenser, three low-pressure feedwater preheaters, three high-pressure feedwater preheaters, a feedwater pump, and a deaerator (Figure 1). The plant operates to generate electricity, utilizing thermal energy produced by the combustion of solid fuel in a pulverized coal-fired boiler. The power output, efficiency, and thermal energy input depend on the current operating conditions and can vary across the power plant's load range. Under selected operating conditions, the main parameters of the analyzed steam power plant are presented in Table 1.

Table 1. Main factors of steam power plant.

Parameter	Unit	Value
Power output	MW	207.8
Thermal power input	MW	501.26
Thermal efficiency	%	41.45 %
Boiler inlet water temperature	°C	221
Steam mass flow rate	t/h	717.5
Steam temperature	°C	537.8
Steam pressure	bar	104.2
Vapour pressure in condenser	bar	0.067

2.2. Concentrated Solar Power (CSP) technology

Solar power collectors have proven to be an innovative and essential technology in the shift towards renewable energy. These devices harness sunlight and convert it into usable electricity, offering a sustainable alternative to traditional energy sources. Their growing popularity stems from several benefits, including the reduction of greenhouse gas emissions and the potential to lower electricity costs significantly. Utilizing solar energy, these systems contribute to global efforts to combat climate change, making them an attractive option for both residential and commercial use. One of the key advantages of solar power collectors is their versatility. They come in various forms, such as photovoltaic (PV) panels, solar power collectors (SPT), and concentrated solar power (CSP) systems. PV panels are the most widely recognized, directly converting sunlight into electricity using semiconductors. On the other hand, solar thermal collectors capture and store the sun's heat to produce hot water or heating for homes and businesses. CSP systems take a more advanced approach, concentrating sunlight to generate high-temperature heat, which drives turbines for electricity production on a larger scale. This diversity allows for various applications, from small household systems to large-scale solar farms. More than 6 GW of concentrated solar power (CSP) plants were installed in 2020 [6], and the largest TES from installed CSP can generate clean electricity for 24 hours by reducing CO₂ emission. The International Energy Agency (IEA) estimates that the CSP will contribute up to 11% of global electricity production in 2050 [6].

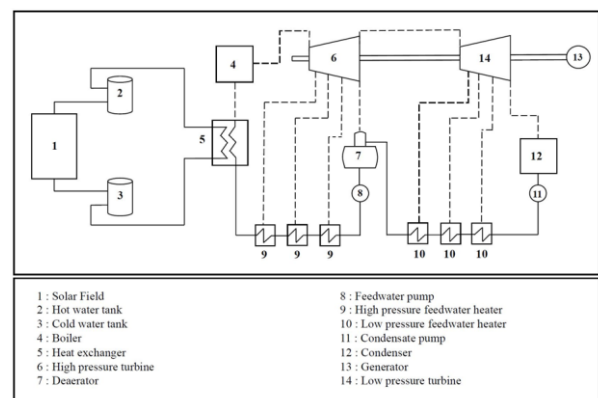


Fig. 1. Schematic layout of the Hybrid Solar Coal Power Plant general concept

3. Modeling of energy systems

3.1. Solar tower receiver and heliostat field

The sun angles and incident power calculations are essential for solar energy applications, particularly in Concentrated Solar Power (CSP) systems. Using the standard DIN 5034, the solar angles, such as the solar altitude and azimuth, is calculated [7]. For solar irradiance, the Direct Normal Irradiance (DNI) is considered and its estimation using the Clear Sky model by Hottel [8] or Clearness Index originally developed by Liu and Jordan [9]. The Clear Sky model estimates DNI for cloudless conditions based on atmospheric

parameters and solar geometry, while the Clearness Index considers cloud cover and atmospheric clarity. These parameters determine the usable solar irradiance and incident power on the receiver aperture.

The total usable solar irradiance \dot{Q}_{usable} is calculated using the formula:

$$\dot{Q}_{usable} = DNI \cdot A_{heliostat} \tag{1}$$

where:

$A_{heliostat}$ - is the total aperture area of the heliostat field, m².

The incident power on the receiver aperture area is calculated as in Eq. (2):

$$\dot{Q}_{incident} = DNI \cdot \rho \cdot A_{heliostat} \cdot \eta_{field}(\gamma_s, \alpha_s) \cdot \eta_{wind} \tag{2}$$

where:

DNI - Direct Normal Irradiance, W/m²

ρ - the average field reflectivity, -

$\eta_{field}(\gamma_s, \alpha_s)$ - solar field optical efficiency depends on the sun azimuth γ_s , and the sun elevation α_s

η_{wind} - wind correction.

The amount of thermal energy transferred to the Heat Transfer Fluid (HTF) by the receiver to raise fluid temperature is calculated using the following formula:

$$\dot{Q}_{eff} = \dot{Q}_{incident} - \dot{Q}_{loss} \tag{3}$$

$$\dot{Q}_{loss} = \dot{Q}_{loss,opt} + \dot{Q}_{loss,conv} + \dot{Q}_{loss,rad} \tag{4}$$

where:

\dot{Q}_{eff} - power of effective heat, kW

\dot{Q}_{loss} - losses composed of optical $\dot{Q}_{loss,opt}$, convective $\dot{Q}_{loss,conv}$ and radiation losses $\dot{Q}_{loss,rad}$, kW.

3.2. Rankine steam cycle

The Rankine cycle power unit is modeled assuming pseudo-steady-state energy balances. The solar and coal-fired components (i.e. boiler, superheater, etc.) are modeled dynamically to account for dynamics in DNI. The entire plant is modeled in Ebsilon Professional software [10, 11]. For all dynamic systems, the built-in integrator block of Ebsilon is used to solve differential equations arising from governing equations. Other major assumptions include neglecting conductive heat transfer, non-axial temperature distributions, and constant condenser operation. Constant values are assumed for saturation pressure during steam generation and isentropic efficiencies for turbomachinery.

3.3. Hybrid energy system

To investigate improvement of steam cycle performance by the use of additional heat source in the cycle, the power output and efficiency of the process were defined. The efficiency of the power plant can be calculated using the following equations:

$$\eta = \frac{N_{el}}{\dot{Q}_F} \tag{5}$$

where:

η - steam cycle fuel-driven efficiency, %

N_{el} - power output, MW

\dot{Q}_F - heat rate to the cycle through boiler (energy from fuel), MW

4. Results and discussion

4.1. Solar field simulation

In the operation of a solar field within a CSP system, solar energy is captured, stored, and transported to enable electricity generation. The input data of Solar Field on 15th June 2021 is presented in Table 2. The process begins with the collection of solar radiation, which is concentrated and transferred to a working fluid. This fluid serves as the medium for storing and transferring thermal energy within the system. The thermal energy is stored in designated units to ensure continuous operation, even during periods when solar radiation is unavailable, such as nighttime or cloudy weather.

Table 2. Solar Field data on 15th June 2021.

Date and time	Power absorbed by the fluid	Effective receiver temperature	Effective field efficiency
12:00:00 AM	0.00 MW	274.71 °C	0 %
2:00:00 AM	0.00 MW	274.71 °C	0 %
4:00:00 AM	0.00 MW	274.71 °C	0 %
6:00:00 AM	46.44 MW	304.78 °C	35.72 %
8:00:00 AM	75.25 MW	323.41 °C	57.25 %
10:00:00 AM	83.91 MW	328.76 °C	63.72 %
12:00:00 PM	87.37 MW	330.86 °C	66.30 %
2:00:00 PM	83.89 MW	328.75 °C	63.70 %
4:00:00 PM	75.22 MW	323.39 °C	57.22 %
6:00:00 PM	46.44 MW	304.78 °C	35.72 %
8:00:00 PM	0.00 MW	274.71 °C	0 %
10:00:00 PM	0.00 MW	274.71 °C	0 %

Table 2 shows that the peak value is obtained during the middle of the day between 12:00 PM and 01:00 PM when the sun is visible at its peak temperature. During the nighttime, the value comes down after the sunset. During these hours, hot storage has to be used to supply heat to the power plant.

4.2. Steam cycle simulation

The steam Rankine cycle power plant operation simulation was designed using Ebsilon® Professional software. The components of the steam cycle in Ebsilon are the steam turbine, steam generator, condenser, pump, deaerator, and preheaters (Figure 2). The three model variants were developed for the simulations, where part of the feedwater before each HP preheater is diverted to the heat exchanger (HE). The hot medium in the HP preheaters is the bleed from stages of HP turbine, and the cold medium is the feedwater from the deaerator to the boiler. The diverted feedwater to the heat exchanger is again mixed with the feedwater line before the boiler inlet, keeping boiler feedwater temperature at the same level.

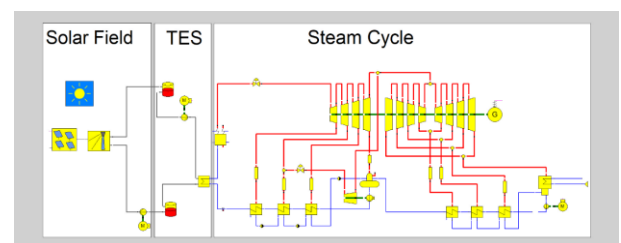


Fig. 2. Model of hybrid solar coal power plant in Ebsilon® Professional.

4.3. Hybrid Solar-Coal Power Plant simulation

The simulation then calculates heat balance to model energy flows through the solar field, thermal energy storage, and steam cycle. Turbine efficiency, fluid properties, and flow rates are meticulously modeled to align with design specifications and ensure efficient system operation.

Three different analyses based on the variants were classified according to the extraction of feed water. A part of the feedwater is extracted before the HP heater and flows through the heat exchanger to utilize solar energy. The flow rate of extracted feedwater is controlled from 10 kg/s to 100 kg/s. The simulated result data are presented and discussed below. The feedwater temperature at the boiler inlet is constant and equal to 221°C. The energy consumed by the steam boiler is also constant in all three variants regardless of the increase in the power generation of the electric generator. Extraction point of the variant 1 (a), variant 2 (b) and variant 3 (c) before HP preheater is shown in Figure 3.

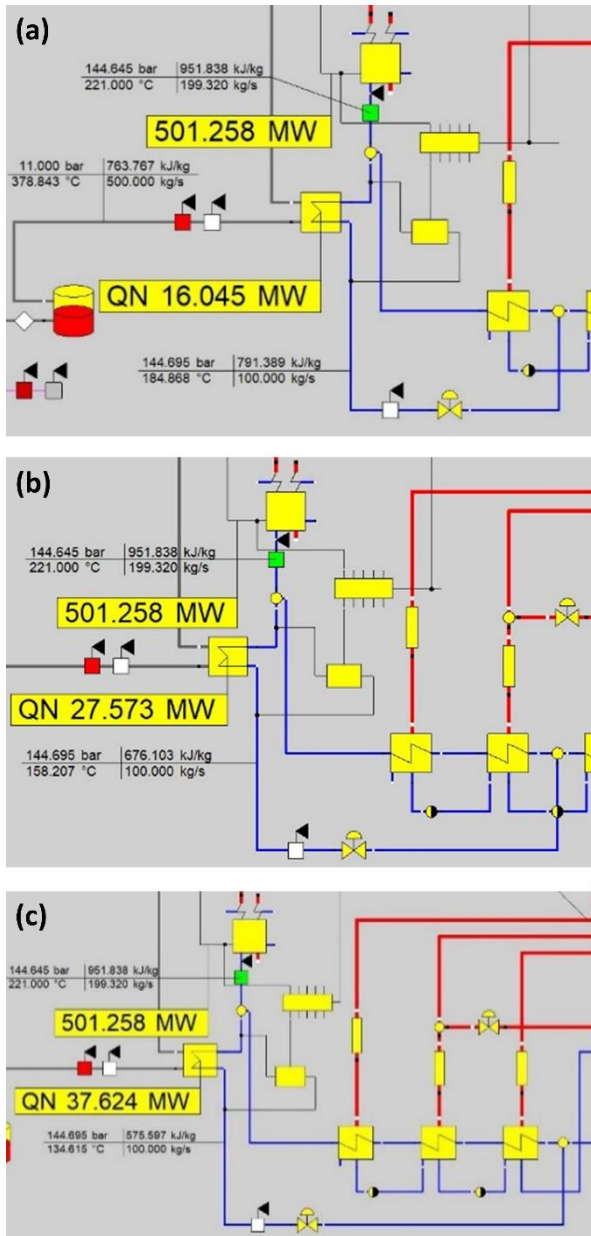


Fig. 3. Extraction point of the variant 1 (a), variant 2 (b) and variant 3 (c) before HP preheater in developed HSCPP model

The hybrid solar-assisted steam power plant simulation demonstrates the successful integration of solar energy with a conventional coal-fired power system. The increase in solar energy input leads to a consistent improvement in thermal efficiency across the analyzed configurations. Compared to results from variants 1 and 2, with efficiencies of 42.58% and 43.25%, this simulated result from variant 3 achieves the highest efficiency of 43.75%.

With a solar contribution of 37.62 MW, the coal consumption needed for generating electricity can be reduced. Although the coal input remains constant, the improved thermal efficiency indicates reduced fuel-specific energy requirements. The increased

integration of solar energy reduces the environmental footprint of the power plant by lowering coal consumption and greenhouse gas emissions. This highlights the potential for hybrid systems to contribute to cleaner and more sustainable power generation.

Table 4. Simulation results for variant 1.

Solar heat input	Power output	Efficiency
MW	MW	%
1.60	208.47	41.59
3.21	209.02	41.70
4.81	209.57	41.81
6.42	210.13	41.92
8.02	210.68	42.03
9.63	211.23	42.14
11.23	211.79	42.25
12.84	212.34	42.36
14.44	212.89	42.47

Table 4. Simulation results for variant 2.

Solar heat input	Power output	Efficiency
MW	MW	%
2.76	208.80	41.66
5.51	209.69	41.83
8.27	210.58	42.01
11.03	211.47	42.19
13.79	212.36	42.36
16.54	213.24	42.54
19.30	214.13	42.72
22.06	215.02	42.90
24.82	215.91	43.07

Table 5. Simulation results for variant 3.

Solar heat input	Power output	Efficiency
MW	MW	%
3.76	209.06	41.71
7.52	210.19	41.93
11.29	211.33	42.16
15.05	212.47	42.39
18.81	213.61	42.62
22.57	214.75	42.84
26.34	215.89	43.07
30.10	217.03	43.30
33.86	218.17	43.52

The relationship between mass flow rate and the efficiency of solar-assisted steam power plant, solar contribution for three variants are illustrated in Figure 4. Overall, the efficiency increases steadily as the mass flow rate rises. At lower mass flow rates (10–30 kg/s), all three variants show relatively low and similar efficiency levels, with Variant 1 performing the least efficiently.

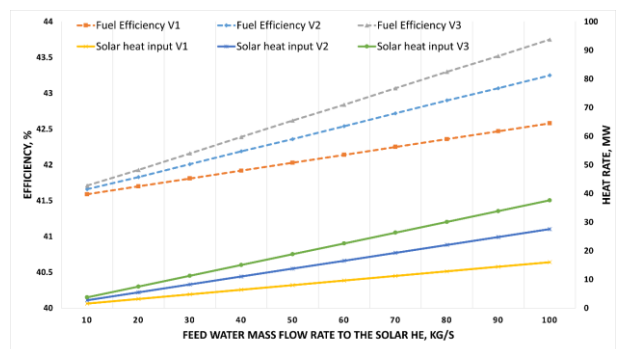


Fig. 4. Efficiency and solar contribution as a function of mass flow rate for all analyzed variants

Variant 1 achieves an efficiency starting at 40.5% at 10 kg/s and peaks just below 43.0% at 100 kg/s. Variant 2 performs moderately better, reaching around 43.25% efficiency at the highest mass flow rate. Variant 3 outperforms both, starting at approximately 41.0% at 10 kg/s and reaching nearly 44.0% at 100 kg/s.

5. Conclusions

The heat absorbed by the fluid from the solar tower receiver varies significantly, ranging from 0 to 86.41 MW, depending on the intensity of solar radiation during operating hours. This variability highlights the intermittent nature of solar energy and the critical role of solar thermal systems in effectively capturing and utilizing solar heat. Despite this variability, the feedwater temperature at the boiler inlet remains constant at 221 °C, ensuring stable operation of the steam cycle and preventing thermal stresses within the boiler system. This stability is achieved by integrating the solar thermal component into the conventional Rankine cycle without disrupting the boiler's operational parameters.

This integration strategy demonstrates the effective utilization of solar energy to supplement and enhance the performance of traditional coal-fired power plants without altering the boiler's energy input, ensuring operational consistency. Such designs improve thermal efficiency and allow for increased electricity generation during peak solar hours, making the hybrid power plant a promising solution for reducing fossil fuel dependence and CO₂ emissions while maintaining reliable power output.

References

- [1] Y. Zhu, R. Zhai, J. Qi, Y. Yang, M. Reyes-Belmonte, M. Romero, Q. Yan, Annual performance of solar tower aided coal-fired power generation system, *Energy* 119 (2017) 662–674.
- [2] F. Liu, T. Lyu, L. Pan, F. Wang, Influencing factors of public support for modern coal-fired power plant projects: An empirical study from china, *Energy Policy* 105 (2017) 398–406.
- [3] M. Hofmann, G. Tsatsaronis, Comparative exergoeconomic assessment of coal-fired power plants–binary rankine cycle versus conventional steam cycle, *Energy* 142 (2018) 168–179.
- [4] S. Gourvenec, F. Sturt, E. Reid, F. Trigos, Global assessment of historical, current and forecast ocean energy infrastructure: Implications for marine space planning, sustainable design and end-of-engineered- life management, *Renewable and Sustainable Energy Reviews* 154 (2022) 111794.
- [5] J. Wu, H. Hou, Y. Yang, E. Hu, Annual performance of a solar aided coal-fired power generation system (sacpg) with various solar field areas and thermal energy storage capacity, *Applied Energy* 157 (2015) 123–133.
- [6] C. S. Power, et al., Technology roadmap concentrating solar power, *Current* 5 (2010) 1–52.
- [7] J. A. Duffie, W. A. Beckman, *Solar engineering of thermal processes*, Wiley New York, 1980.
- [8] H. C. Hottel, A simple model for estimating the transmittance of direct solar radiation through clear atmospheres, *Solar energy* 18 (2) (1976) 129–134.
- [9] B. Y. Liu, R. C. Jordan, The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Solar energy* 4 (3) (1960) 1–19.
- [10] <https://www.ebsilon.com>
- [11] P. Madejski, P. Żymelka, *Introduction to computer calculations and simulation of energy systems operation in STEAG Ebsilon@Professional* (in Polish). The AGH University of Science and Technology Press, Kraków, 2020.

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