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Thermal analysis of an integrated solar combined cycle power plant and its application in southern Iraq

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ABSTRACT

Recently, simple cycles have played an essential role in generating electricity in Iraq. However, these devices suffer from low thermal efficiency and low power output. In the present work, a theoretical study was conducted with the aim of improving the performance of (the AL-Amara power plant 125 MW). The current work consists of three parts: The first part focuses on the impact of ambient temperature on the performance of simple circuits, including mass flow, power output, thermal efficiency, and other parameters. In the second part, modifications from simple to combined cycles are implanted. The third part examines the benefits of using solar systems to produce more steam to feed heat recovery steam generators, which hope to generate more electricity and reduce emissions. For a simple gas turbine installation, the results show that the mass flow rate decreases almost (10.8%) as the ambient temperature increases from (15-50) °C. However, the reduction in air mass flow significantly reduced power output and thermal efficiency (22.6% and 13.2%, respectively). In the second part, the application of the combined mode shows significant improvements in power output and thermal efficiency (32.5% and 32.3%, respectively). The specific fuel consumption dropped by nearly 32.19%. Finally, in the third part, the collected results show that there is an acceptable increase in the amount of steam generated by the solar system (21.02 kg/s) when using the solar system. The overall performance of the integrated cycle shows that the power output and thermal efficiency are almost improved (11.28% and 10% respectively)

1. Introduction

The worldwide energy demand in developing countries is growing significantly because of industrial expansion, high population, and economic growth [1]. Thermal power plants, like "steam power plants, gas turbines, and diesel engines "play an important role in meeting this demand. The use of simple gas turbines for power generation has increased in recent decades and is expected to continue in the near future due to the capital cost of power ratio, and the high flexibility and reliability achievable.

The disadvantages of these units, most of the thermal energy produced by the combustion of hydrocarbon fuel is expelled to the atmosphere in the form of heat energy since only 29-38% of the total thermal energy is converted to useful work "power output". Gas turbine generator thermal efficiency can be improved by up to 60 % [2] [3] by recovering and using the waste heat from the gas turbine exhaust gases. This technique is known as called combined cycle gas turbine (CCGT).

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Nomenclature:

A	area
Cp	Specific heat at constant pressure
con	Condenser
dea	Deaerator
G_{cb}	intensity of direct solar radiation
h	Enthalpy (kJ/kg)
HP	High pressure stage
LCV	Lower calorific value of fuel (kJ/kg)
LP	Low pressure stage
$\dot{m}$	Mass flow rate (kg/s)
Pe	Power output
$\dot{Q}$	heat rate (kw)
SFC	Specific fuel consumption (kg /kw.hr)
SH	Super heater
T	Temperature (°C)
$\dot{V}$	Volumetric flow rate (m^3/s)
ECO	Economizer
EV	Evaporator
W	The work (kJ)

Greek symbols

ρ	density (kg/m^3)
$\eta_{m,p}$	mechanical efficiency of the pump
$\eta_{m,ST}$	mechanical efficiency of the steam turbine

Subscripts

c	Compressor
cc	Combustion chamber
f	fuel
g	Gas
GT	Gas Turbine
m	Mechanical
s	steam
sf	solar field
tot	total

Normally the cycles can be classified as topping and bottoming cycles as shown in Fig.1. In the combined cycle process exhaust gases from (GT) pass in HRSG to heat water and produce superheated steam without the usage of any additional fuel. Therefore, fuel consumption occurs only in (GT) combustion chambers. Moreover, introducing solar units for generating steam may contribute to increase power and improve thermal efficiency. Integrated Solar combined cycle system (ISCC) are modern combined cycle power plants with gas and steam turbines and additional thermal input of solar energy from a solar receiver system.

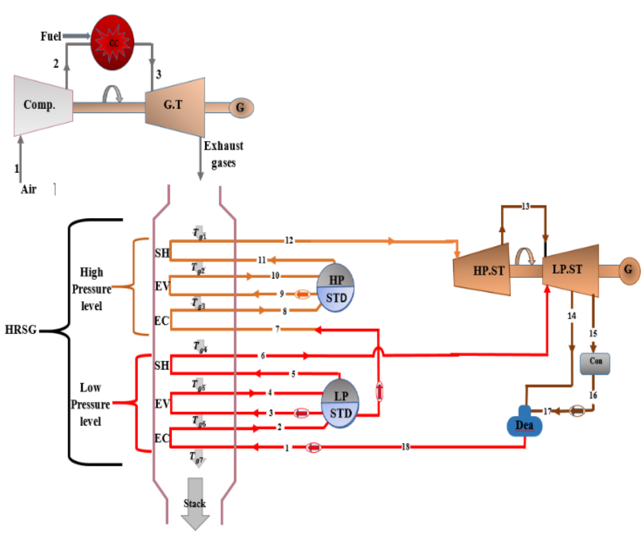

Figure 1. Combined cycle gas turbine

1.1 Principle of CCGT

A combined cycle power plant consists of at least one gas turbine (GT) units, at least one steam turbine (ST) unit, and its connection by heat recovery steam generator (HRSG) [4]. The idea of combining gas and steam turbine processes arises from the high temperature and high mass flow rate of flue gases, which exit the gas turbine generator. Simple gas turbine units consist of three primary open systems, a compressor, combustion chamber and gas turbine section [5]. The basic principle of operation of mainly simple gas units involves several process, drawing air from the ambient environment to be compressed by the compressor, compressed air is directed to enter the combustion chamber where combustion of fuel is take place. The hot gases leaving the combustion chamber at high temperature are enter the turbine unit. The turbine allows the gases to expand inside, and as a result of this process a mechanical work is obtained which is converted into electrical energy via an electric generator. Hot gases leaving the turbine is expelled to the atmosphere carrying a significant quantity of thermal energy.

In the present work a thermal analyses would be current out to observe the performance of simple cycle, combined cycle and integrated cycle. In combined cycle, the exhaust gases leaving the gas turbine have a significant thermal energy which can be recovered by a heat recovery steam generator to produce superheated steam. This superheated steam of high pressure and temperature will be directed to steam turbine for generating extra electric power without the usage of any additional fuel. Therefore, fuel consumption occurs only in GT combustion chambers. A dual pressure heat recovery steam generator is adopted in this study which is consists mainly of six heat exchangers, three for the high pressure and three for the low pressure as shown in Fig. 2.

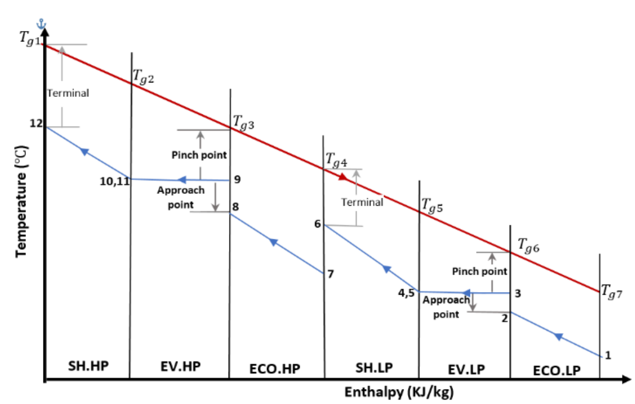

Figure 2. Dual HRSG

2.Thermal analysis

Simply, three thermal systems would be studied in the work, the first is a simple cycle gas turbine with no modification, the second system is combined gas turbine cycle (simple gas, HRSG and steam turbine) and finally the integrated solar combined cycle. Mass and energy conservation laws were applied to each system by Engineering Equation Solutions (EES) software.

2.1 Simple gas turbine

A simple gas turbine unit consist of compressor, combustion chamber and a turbine as shown in Fig. 3. Air is drawn by the compressor and compressed to high pressure, then directed to combustion chamber where it mixed with fuel and combustion occurs at constant pressure (continuous combustion). Hot gases leaves the combustion chamber turbine enters the turbine at high pressure and temperature through the cycle which expand completely to atmospheric pressure, exhaust gases (with high thermal energy).

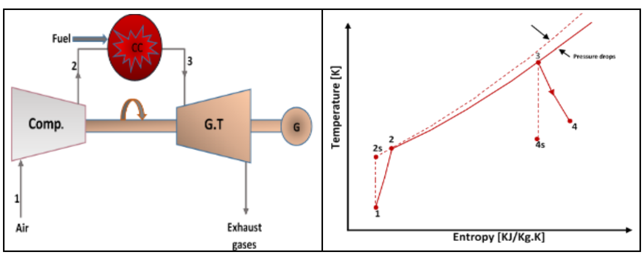

Figure 3. Simple Cycle Gas turbine (SCGT) Unit

The work of the Compressor can be calculated using the following equation:

$$W_c = m_a \times (h_2 - h_1) \quad (1)$$

However, the combustion chamber of the gas turbine unit, it consists of fourteen secondary combustion chambers distributed in a circular manner, in which the fuel combustion process takes place.
The amount of heat supplied by the fuel in the combustion chamber can be obtained from the following equation:

$$\dot{Q}_{23} = \dot{m}_g \times \ (h_3 - h_2)\,.\eta_{cc} \quad (2)$$

The work of turbine can be calculated using the following equation:

$$\dot{W}_{GT} = \dot{m}_g\ (h_3 - h_4) \quad (3)$$

The power out put of simple gas unit (SCGT) power plant can be calculated from the following equation

$$Pe_{SCGT} = W_{net}\ \eta_m \quad (4)$$

The thermal efficiency of $(SCGT)$ power plant is given by the following equation:

$$\eta_{SCGT} = Pe_{SCGT}/(\dot{m}_f \times \mathrm{LCV}) \quad (5)$$

Moreover, the specific fuel consumption of $(SCGT)$ calculate from equation

$$SFC_{SCGT} = (\dot{m}_f \times 3600)\ /Pe_{SCGT} \quad (6)$$

The mass flow rate of air which is entered to the compressor can calculated by the following equation.

$$\dot{m}_a = \rho_a\ \dot{V} \quad (7)$$

2.2 Thermal analysis of (HRSG)

A heat recovery steam generator (*HRSG*) is an energy recovery heat exchanger that recovers heat from a hot gas stream, such as a combustion turbine or other waste gas stream. It produces steam that can be used in a process used to drive a steam turbine (HRSG) are classified to (Single pressure, Dual pressure and Multiple pressure) steam generator system [6] . depending on the type of (design, the method of connecting the system to the exhaust gas stream), and each type has characteristics, each of this pressure levels contains on (economizer, evaporator, and super heater) Represented [7] the first step to simulate of the (HRSG) is to balance energy andthe mass between the hot stream and feed water on different heat exchangers. can clarify about energy balance by using the following equation [8]. The energy balance of high pressure stage is:

$$(\dot{Q}_{SH})_{HP} = \dot{m}_{ss}(h_{12} - h_{11})_{HP} = \dot{m}_g\,Cp_g\ (T_{g1} - T_{g2}) \quad (8)$$

$$(\dot{Q}_{EV})_{HP} = \dot{m}_{sat}(h_{10} - h_9)_{HP} = \dot{m}_g\,Cp_g\ (T_{g2} - T_{g3}) \quad (9)$$

$$(\dot{Q}_{ECO})_{HP} = \dot{m}_w(h_8 - h_7)_{HP} = \dot{m}_g\,Cp_g\ (T_{g3} - T_{g4}) \quad (10)$$

And the energy balance of low pressure stage is:

$$(\dot{Q}_{SH})_{LP} = \dot{m}_{ss}(h_6 - h_5)_{LP} = \dot{m}_g\,Cp_g\ (T_{g4} - T_{g5}) \quad (11)$$

$$(\dot{Q}_{EV})_{LP} = \dot{m}_{sat}(h_4 - h_3)_{LP} = \dot{m}_g\,Cp_g(T_{g5} - T_{g6}) \quad (12)$$

$$(\dot{Q}_{ECO})_{LP} = \dot{m}_w(h_2 - h_1)_{HP} = \dot{m}_g\,Cp_g\ (T_{g6} - T_{g7}) \quad (13)$$

Assumed the Mass flow rate of working fluid in (ECO, EV, SH) are equal in each pressure level

2.3 Energy Analysis of steam turbine

Steam units are the most common technology used in power plants and industries. It was invented in (1884) by Sir Charles Parsons [9]. About 80% of the world's electricity is produced by use the Steam turbines. In this study the steam turbine consists of two stages. The superheated steam enters the turbine at suitable pressure and temperature and expands through steam turbine stages to derive the steam turbine and produce further power production with the aid of the generator. steam unit consists of a steam turbine, a condenser, a pump, and a deaerator. Fig. 4 shows the relationship between temperature and entropy for each part of the steam unit.

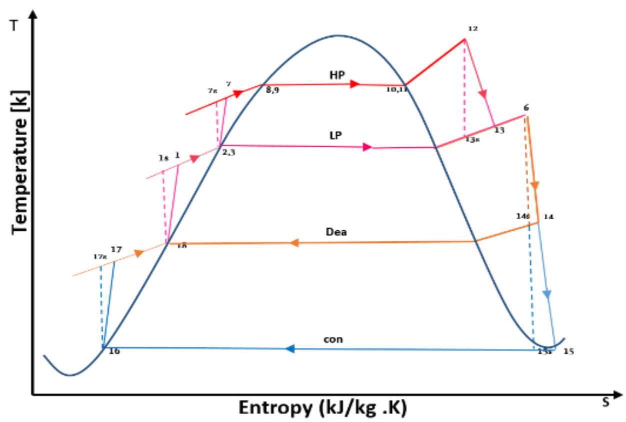

Figure 4. the relationship between temperature and entropy in the steam generation system

To calculate the total work produced by the steam turbine, where it represents the total work in the high and low pressure stage, using the following equations:

$$\dot{W}_{ST} = \dot{W}_{HP,ST} + \dot{W}_{LP,ST} \quad (14)$$

$$\dot{W}_{HP,ST} = \dot{m}_{s,HP}\,(h_{12} - h_{13}) \quad (15)$$

$$\dot{W}_{LP,ST} = \dot{m}_{s,tot}\,(h_6 - h_{14}) + (\dot{m}_{s,tot} - \dot{m}_{dea})\,(h_{14} - h_{15}) \quad (16)$$

The total work of the pumps is calculated based on the equation:

$$\dot{W}_{p,tot} = \dot{m}_{s,HP} \times (h_7 - h_3) + \dot{m}_{s,tot} \times (h_1 - h_{18}) + (\dot{m}_{s,tot} - \dot{m}_{dea}) \times (h_{17} - h_{16}) \quad (17)$$

The net work of the steam unit can be calculated through the following equation:

$$\dot{W}_{net} = \dot{W}_{ST} - \dot{W}_{p,tot} \quad (18)$$

The steam turbine power output can be obtained as follows:

$$Pe_{ST} = (\dot{W}_{net} \times \eta_{m,ST}) - (\dot{W}_{p,tot} \times \eta_{m,p}) \quad (19)$$

2.4 Energy analysis of (CCGT)

The benefit of applying combined cycle mode to simple gas turbines can be obtained through out the following equations [10].

$$Pe_{CCGT} = Pe_{SCGT} + Pe_{ST} \quad (20)$$

$$\mathrm{SFC}_{CCGT} = (\dot{m}_f \times 3600)\,/Pe_{CCGT} \quad (21)$$

$$\eta_{CCGT} = Pe_{CCGT}/(\dot{m}_f \times LCV) \quad (22)$$

2.5 Energy of Integrated solar combind cycle (ISCC)

Three main components of a typical integrated solar combined cycle (ISCC) units which are gas turbine generator, steam turbine unit, heat recovery steam generator (HRSG) unit and solar field. Solar field consists of solar collectors and solar steam generator (SSG). The most commonly solar collectors used in the ISCC are parabolic trough type [11], which is assumed in this present work. The operating of the ISCC is derived from the combined cycle power plant, where the hot exhaust gases from the gas turbine are used to generate steam in the HRSG, which is used to develop steam from the steam turbine. While additional amount of steam is generated in the SSG (solar steam) to supplement the steam being produced in HRSG [12]. Hence, part of the feed water will preheated in the HRSG (economizer) before entering the solar steam generator, where it is converted to saturated steam. This saturated steam is redirected to the HRSG where it is superheated by the exhaust gases departure the turbine units [13]. At night, the power plant operates as a combined cycle unit since, so the thermal energy storage is not considered in the proposed system. The total power output from the (ISCC)can be assessed by the following equation.

$$\mathrm{Pe}_{\mathrm{ISCC}} = \mathrm{Pe}_{sf} + \mathrm{Pe}_{\mathrm{CCGT}} \quad (23)$$

Moreover, the efficiency of the (ISCC), can be calculated using the following equation

$$\eta_{ISCC} = \mathrm{Pe}_{\mathrm{ISCC}}\,/(\dot{m}_f \times \mathrm{LCV} + A_{sf} \times G_{cb}) \quad (24)$$

3. Results and discussions

An energy analysis were carried out for each cycle configuration, simple cycles, combined cycle and integrated solar cycle. Regarding to the simple cycle mode, Fig. 5 show the variation of the power output of air ambient temperature. It can be seen that power output decrease nearly by (22.6%) when the ambient temperature increase from (15℃-50℃). Fig. 6 show the effect of ambient temperature on the thermal efficiency of the simple cycle. It is found that the thermal efficiency decrease nearly by (13.2%) as the ambient temperature increases from (15℃-50℃). While the specific fuel consumption as shown in Fig. 7 increases nearly by (13.27 %) due to the decrease in the power output. A combined-cycle gas turbine (CCGT) power plant uses the exhaust heat from gas turbines to generate steam with a heat recovery steam generator (HRSG). The produced steam is then fed to a steam turbine to provide additional power output. Fig. 8, shows that the value of the additional power which obtained from the application of the combined cycle mode is nearly (60.295 MW). Fig. 9 shows that the thermal efficiency increase nearly (32.3%) when the simple cycle is converted to combined gas turbine cycle. This can be explained as a result of the exploitation of the wasted thermal energy by the steam generation system to produce superheated steam that is used by the steam turbine to generate additional power.

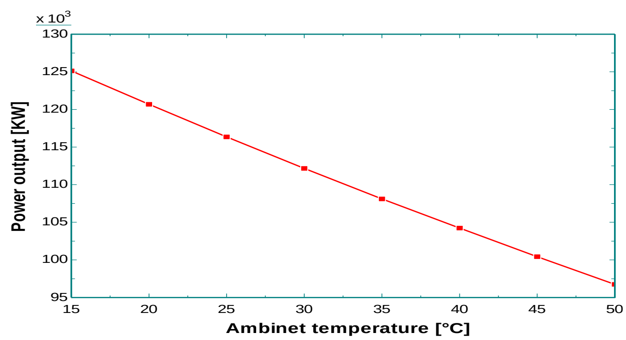

Figure 5. SCGT outputs

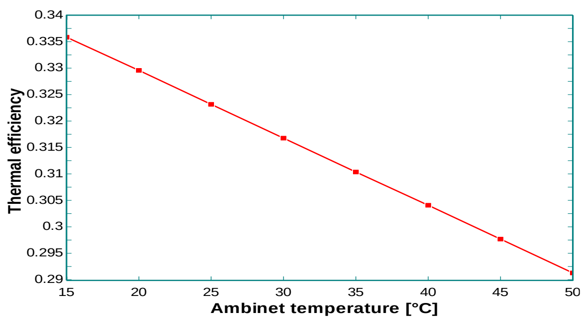

Figure 6. thermal efficiency of (SCGT)

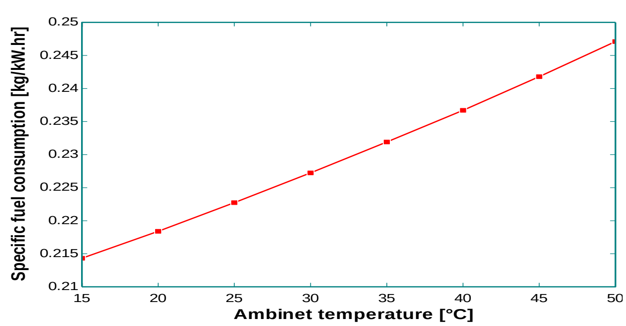

Figure 7. specific fuel consumption of (SCGT**)**

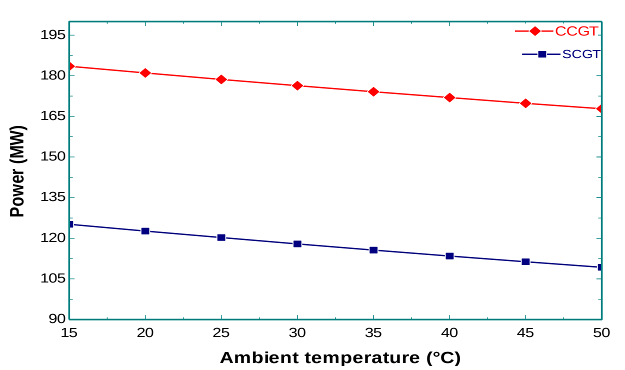

Figure 8. CCGT outputs

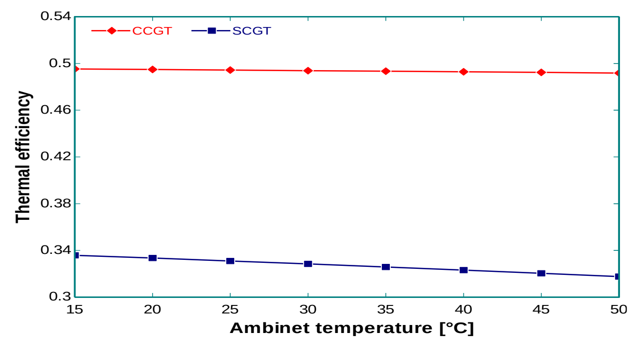

Figure 9. CCGT efficiency

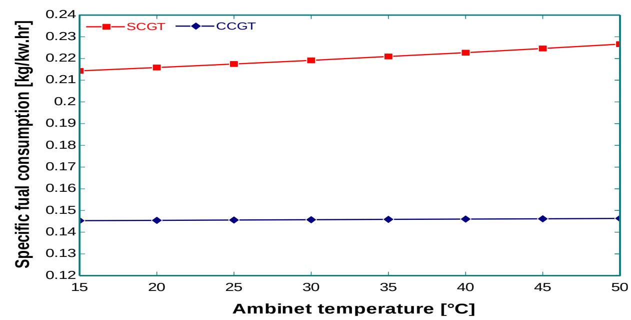

Figure 10. CCGT of specific fuel consumption

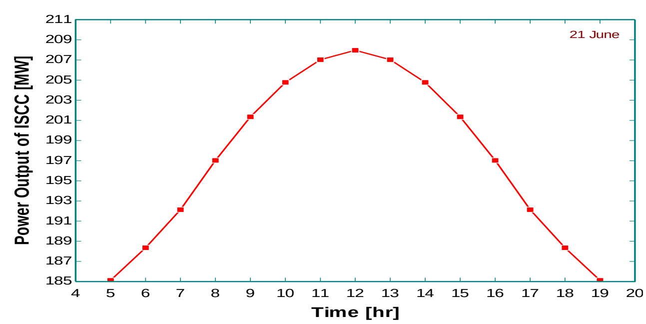

Figure 11. The power output of (ISCC)

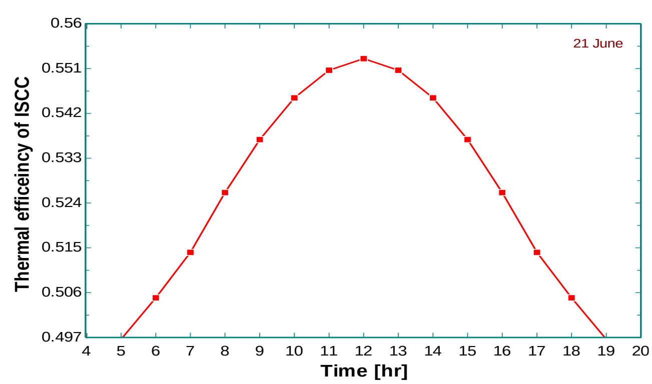

Figure 12. thermal efficiency of (ISCC

4. Conclusion

Currently, the most efficient energy conversion technology combines a gas turbine generator with a steam turbine loop in a heat recovery steam generator. The main conclusions of the current study are as follows:

i. Increases in ambient temperature can affect the performance of simple gas installations, and combined and integrated systems.
ii. Applying the combined cycle mode to the simple cycle, the power output and thermal efficiency are significantly increased by almost (32.5 and 32.3% respectively). The fuel consumption rate is almost reduced (32.19%) compared to the simple gas unit.
iii. As the amount of steam generated by the solar farm increases and is delivered to the power station, the integrated solar combined cycle plant's peak power output and thermal efficiency increase to (209 MW) and the mid-day thermal efficiency increases to (55.3%). Heat recovery steam generator (HRSG).
iv. At night, since no thermal storage system is installed, the system works like a conventional combined cycle power plant.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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