Heat Rate And Economic Evaluation Of A Photovoltaic-Assisted Combine Cycle Power Plant

Klahan Suksawai and Pongsakorn Kachapongkun*

Rattanakosin Collage for Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin, Nakhon Pathom, Thailand

* *Corresponding author. E-mail: pongsakorn.kerd@rmutr.ac.th*

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Gas turbine combined cycle (GTCC) power plants are widely used as major power plants in grid systems, while world energy prices are rather high and renewable energy is now stepping in to replace conventional fossil energy. Therefore, the efficiency of the GTCC needs to be improved for both thermal efficiency and economic aspects. This concept will help GTCC improve its heat rate by bringing in renewable energy. In the present research, the installation of solar photovoltaics (PV) in the GTCC power plant for supplying the auxiliary equipment of the power plant was studied. The heat rate comparison between the proposed method and conventional GTCC, including an economic evaluation, was conducted through a case study of an independent power producer operating a 700 MW GTCC in Thailand. The performance test and calculation methodology followed the Performance Test Code 46 of the American Society of Mechanical Engineers, which eliminated the uncontrollable impact of environments. As a result, the PV system could replace some of the auxiliary power consumption by utilizing a PV system of 980 kW, the GTCC heat rate was improved to 59.17 kJ/kWh, and the electrical power generation was 1,393,379 kWh per year, which reduced the natural gas consumption by 10,086,671 MJ annually or 100,867 GJ for the remaining lifetime of the power plant.

Keywords: Combine cycle, Photovoltaics, Auxiliary power consumption, Economic

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1. Introduction

The world's energy price today is highly fluctuating, and there is a tendency for it to drastically grow, resulting in an acceleration of development and improving the thermal efficiency of conventional fossil power plants (CFPP) by reducing the heat rate (HR) in order to reduce the cost of fuel. Together with the step toward renewable energy (RE) and the tendency toward clean energy, which influences electrical power generation, the share of electricity production from RE has grown rapidly [1]. Due to the depletion and high price of fossil fuel and the unlimited availability of RE, there is an idea to integrate these two sources of natural energy together; therefore, improving the thermal efficiency by integrating solar energy with CFPP is the focus of current research.

Hybrid solar and CFPP have been studied by various researchers; most of them proposed integrating solar thermal energy with CFPP to increase the thermal efficiency of CFPP. Hybrid solar electrical power generation can improve coal-fired electrical power plant efficiency by saving extraction steam that goes through the turbine, and as a result, electrical power generation and plant performance are increased [2].

Ameri and Mohammadzadeh [3] evaluated three scenarios of solar cycle location in the steam bottoming cycle of the combined cycle power plant. The outcome of the proposed integrated solar combined cycle power plant has proven to be one of the power plants with the lowest cumulative energy demand among other studied methods of electricity generation. Abdelhafidi et al. [4] conducted simulations and experiments on the Hassi R'mel power plant, which is the first hybrid solar-gas power plant in Algeria.

The result showed that the overall thermal efficiency of the combined cycle can be increased to 64.2% and 55.7% with the integration of the solar field in typical system operations during the summer and winter seasons, respectively. A full-day dynamic characteristics analysis of a solar-aided coal-fired power plant [5] was studied, and the results indicated that with the control strategy of maintaining the solar field outlet heater fluid temperature constant, the main operating system could operate within the safety ranges. Furthermore, during a full day, both the total solar power output and the CO_2 emission reduction were 207.7 MWh and 186.7 tons per day, respectively. Solar PV was also considered to mix with other renewable energy sources, such as wind energy conversion systems (WECS), to simulate the performance characteristics of the hybrid solar PV and WECS under varying temperatures, irradiation, and wind speeds. The integration of these two sources results in a highly efficient and reliable system [6]. There is not only the advantage of performance improvement, but hybrid solar PV-aided coal-fired power plants can avoid solar curtailment, which is a challenging issue to be solved for standalone PV power generation systems [7].

From an economic point of view, Khankari and Karmakar [8] studied power generation from flue gas waste heat in a 500 MW thermal power plant using solar assisted. The results revealed that the payback period and internal rate of return of the proposed system at optimum operating parameters were 12.44 years and 7.11%, respectively. Furthermore, net present value (NPV), internal rate of return (IRR), and payback period (PBP) are considered to ensure the investment return. One of the main economic indices to show the cost-effectiveness of the newly developed energy systems is the PBP. To determine the PBP of the proposed combined heat and power system, the NPV method is utilized [9].

In order to improve the thermal efficiency of electrical power plants, solar energy is widely used to integrate with CFPP. In the case of Thailand, most of the electrical power plants, or 52% of the installed capacity, are GTCC power plants, where natural gas (NG) is a major fuel for electricity generation [10]. Furthermore, most of their contract capacity is around 700 MW. Therefore, the idea to utilize solar energy to integrate with GTCC is convincing, anyway, due to the fact that GTCC power plants in Thailand have mostly been in service under guaranteed power purchase agreements (PPA), in which maintenance outages or shutdown times have been strictly mentioned in the PPA. As a result, modifications to integrate solar thermal energy to assist GTCC that take a long time are not encouraged. However, instead of using solar thermal energy, solar PV has the advantage of taking a shorter time to modify and being less complicated to install compared to solar thermal energy. Hence, a solar PV-assisted GTCC power plant is one of the solutions and is compatible with Thailand's PPA contract. Besides, by using a PV-assisted GTCC power plant, electricity from solar PV can be consumed even when the GTCC power plant is in operation or on shutdown, unlike solar thermal energy, which can be utilized only when the GTCC power plant is in operation. Therefore, it is interesting for this research to focus on a new concept to integrate a solar PV system onsite at the GTCC power plant. The assumption is that the GTCC power plant heat rate will be reduced by fuel gas consumption reduction from MW output or electricity generated by GTCC. The reduced electricity generation by GTCC is compensated by solar PV.

2. Theory and formula

2.1. Gas Turbine Combine Cycle power plant

Combined-cycle power plants use a combination of gas and steam turbines to produce up to 50% more electricity from the same fuel than a traditional simple-cycle power plant. In Fig. 1, the major components of GTCC are shown: the gas turbine drives an electrical generator as a topping cycle, and waste heat from the turbine exhaust is delivered to the nearby steam turbine to provide supplemental electricity as the bottoming cycle. The basic idea is that when the gas turbine engine has finished its cycle, the exhaust is still hot enough for a second, succeeding heat engine to use to generate energy. In order for the two engines to use separate operating fluids, the heat is often transferred through a heat exchanger called a heat recovery steam generator (HRSG), then water inside the HRSG transforms into steam, and through a steam turbine, which is coupled with an electric generator, steam, after transferring energy to the turbine, will go down to the condenser and transform back into water [11–13]. The overall thermal efficiency of a combined cycle is practically 60%, a substantial improvement over the efficiency of a simple, open-cycle application of around 30% [14].

2.2. Heat rate and Efficiency of power plant

Heat rate is one measure of the electrical generators efficiency of power plants that convert a fuel into heat and into electricity. The heat rate is the amount of energy used

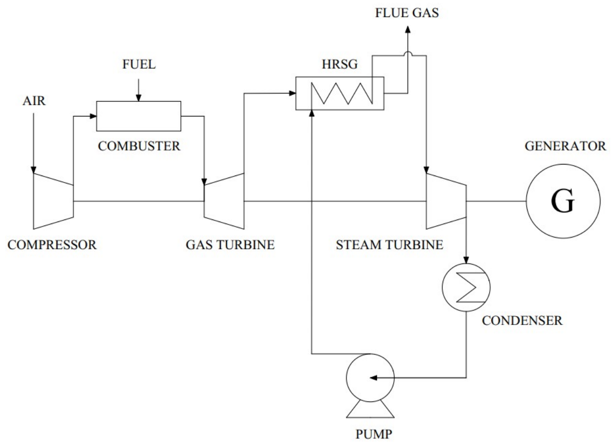

Fig. 1. Schematic of the Gas Turbine Combine Cycle power plant.

by an electrical generator of power plant to generate one kilowatt-hour (kWh) of electricity [15]. Heat rate is also the inverse of plant efficiency, in this sense, the better the efficiency, the lower the heat rate.

$$\text{Heat Rate} = \frac{\text{Input Energy}}{\text{Output Energy}} \tag{1}$$

Normally, the overall heat rate (kJ/kWh) for the combined cycle is calculated by taking the heat consumption of the fuel burned in each of the gas turbines in kJ and dividing it by the total generation (kWh) from the gas turbine generator and the steam turbine generator, which is called "gross heat rate," or even dividing the total heat consumption by net generation, which is "net heat rate" [16, 17]. Net generation is the amount of electricity a power plant supplies to the power transmission line connected to the plant. Net generation accounts for all the electricity that the power plant consumes to operate the generator and other equipment, such as fuel feeding systems, boiler water pumps, cooling equipment, and pollution control devices.

$$NHR_m = \frac{\text{Input Energy}}{\text{Net Output Energy}} \tag{2}$$

Where NHR_m is measured net heat rate of GTCC power plant (kJ/kWh); Net Output Energy is electric energy after deducted by auxiliary energy or electric energy measured at revenue meter before sending to grid system (kWh); Input Energy is energy from fuel burned supply to GTCC power plant (kJ).

The input energy can be determined in term of fuel gas flow consume by gas turbine and heating value of such natural gas as follows [16, 17].

$$\text{Input energy} = V_b \cdot HHV \tag{3}$$

Where HHV is high heating value of natural gas (kJ/kg); V_b is calculate total fuel gas flow supply to gas turbine (kg/h). According to this study, the flow meter to measure natural gas flow supply to gas turbine is turbine flow meter, hence fuel gas flow can be determined as follows [16, 17].

$$V_b = V_{f_c} \cdot \gamma_b \cdot \left(\frac{P_f}{P_b}\right) \cdot \left(\frac{T_b}{T_f}\right) \cdot \left(\frac{Z_b}{Z_f}\right) \tag{4}$$

Where γ_b is gas density at base condition from ISO1976:1995 $\left(\mathrm{kg/m^3}\right)$; P_f is static pressure of fuel gas at flowing conditions (MPA(a)); P_b is static pressure of fuel gas at base conditions $(= 0.101325\mathrm{MPA(a)})$; T_f is absolute temperature of fuel gas at flowing conditions (K); T_b is absolute temperature of fuel gas at base conditions (K); Z_f is compressibility factor of fuel gas at flowing conditions (from AGA report No.8); Z_b is compressibility factor of fuel gas at base conditions (from AGA report No.8); and V_{fc} is correct total fuel gas flow during performance test $\left(\mathrm{m^3/h}\right)$ which can be calculated as follows [16, 17].

$$V_{fc} = V_f \cdot \frac{(100 - \Delta V_{cal})}{100} \tag{5}$$

Where ΔV_{cal} is flow deviation from actual fuel gas flow as per calibration result from laboratory (%); V_f is measure total fuel gas flow during performance test $\left(\mathrm{m^3/h}\right)$, hence measure total fuel gas flow can be determined as follows [16, 17].

$$V_f = \frac{\left(N_{\text{pulse,end}} - N_{\text{pulse,start}}\right)}{K_{\text{factor}}} \tag{6}$$

Where $N_{\text{pulse,start}}$ is measure pulse signal of flow meter at the start point of the test (pulse); $N_{\text{pulse,end}}$ is measure pulse signal of flow meter at the end point of the test (pulse); K_{factor} is K-factor of the flow meter (shop calibration value pulse $/\mathrm{m}^3$).

Anyway, GTCC power plants are used to generate power and design based on required conditions, but actually inlet conditions cannot control as per the designed conditions. Combustion turbine performance changes with ambient conditions, which are the dominant cause of changes from the design reference conditions. In this paper, GTCC heat rate need to be compared and in order to eliminate uncontrol from ambient conditions affect to GTCC heat rate calculation result, correction curve from machine manufacturer is used to correct back performance of GTCC to reference condition. Therefore, calculated heat rate after corrected back to the same reference condition

Table 1. Site Reference Condition.

Site Reference Condition	value
Ambient air temperature	32.2°C
Atmospheric pressure	1010mbar
Relative humidity	75%
Excess air filter total pressure loss	100mmAq
Excess exhaust duct total pressure loss	390mmAq

can be compared. These conditions include ambient air temperature, atmospheric pressure, relative humidity, access air filter total pressure loss and access exhaust duct total pressure loss. These reference conditions are shown in the Table 1 [16, 17].

Thus, net heat rate of GTCC power plant NHR_m according to Eq. (2) is adjusted by correction curve from manufacturer as follows [16, 17].

$$NHR_c = \frac{NHR_m}{H_1 \times H_2 \times H_3 \times H_4 \times H_5} \tag{7}$$

Where NHR_c is corrected net heat rate at site reference condition (kJ/kWh); H_1 is correction factor for ambient temperature; H_2 is correction factor for barometric pressure; H_3 is correction factor for relative humidity; H_4 is correction factor for access inlet air filter total pressure loss; H_5 is correction factor for access exhaust duct total pressure loss.

Net heat rate is better reflected overall efficiency of electrical power plant compares to gross heat rate due to there is some portion of generated electricity from generator of gas turbine or steam turbine has been reverted to power plant for internal used. If such internal electricity used is more, there will be lower utilize electricity send to the grid system, hence measured electricity sends to the grid system at revenue meter directly reflect efficiency of power plant. The internal used electricity in power plant usually calls "Auxiliary power".

2.3. Auxiliary power for power plant

The electricity from the power plant has to supply not only the grid system but also auxiliaries that keep the power plant up for a certain period [18]. The function of the auxiliary power system is the distribution and control of electrical energy to the station's auxiliary plant. Auxiliary power is electric power that is provided by an electric generator in the power plant itself or imported electrical power from the system grid that serves as backup for the primary power source at the station's main bus or prescribed sub-bus. For GTCC, auxiliary load means power used to operate auxiliary equipment and the facilities necessary for power generation such as pumps, blowers, fuel preparation machinery, exciters, cooling fans, air conditioners, lights, computer systems, etc., as shown in Fig. 2. Total plant auxiliary consumption is divided into two broad categories: plant-generated auxiliary (when the power plant is in operation) and total import (when the power plant is shut down).

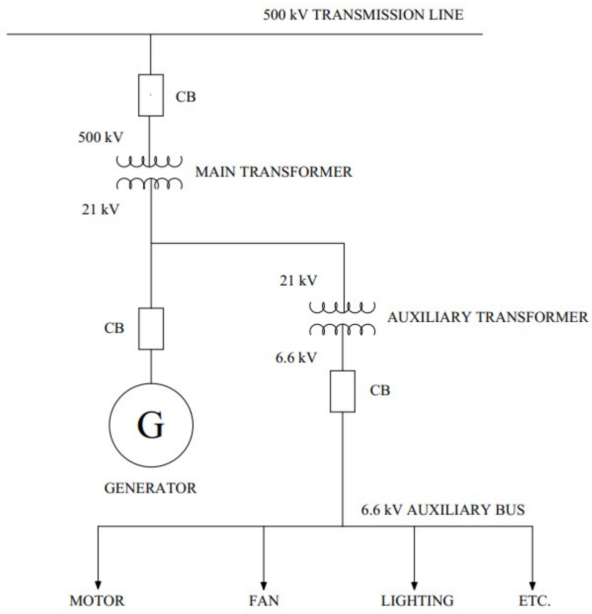

Fig. 2. Schematic diagram of auxiliary power in GTCC.

The auxiliary power consumption or internal used electricity in GTCC is usually supplied by gas turbine or steam turbine generators when the power plant is in service, but whenever the power plant is put on shutdown, such internal used electricity is still needed; therefore, imported electricity from the grid system needs to be sent back to supply necessary equipment in the power plant as backup or reserve power. In GTCC power plants, the auxiliary power consumption is in the range of 2 to 5% of the actual generating capacity [19].

2.4. Solar PV electricity generation

The average solar light intensity in Thailand is 18–20 megajoules per square meter per day [20]. Figure 3 shows On Thailand's solar resource map, there is a high PV potential area in the northeastern and middle of the country [21]. In 2021, the total capacity of solar energy in Thailand will reach approximately 3,049 MW. The capacity of solar energy in the country has continuously increased in the past ten years [22].

According to National Renewable Energy Laboratory (NREL) [23], PV output generation EN_{AC} is calculated as follows:

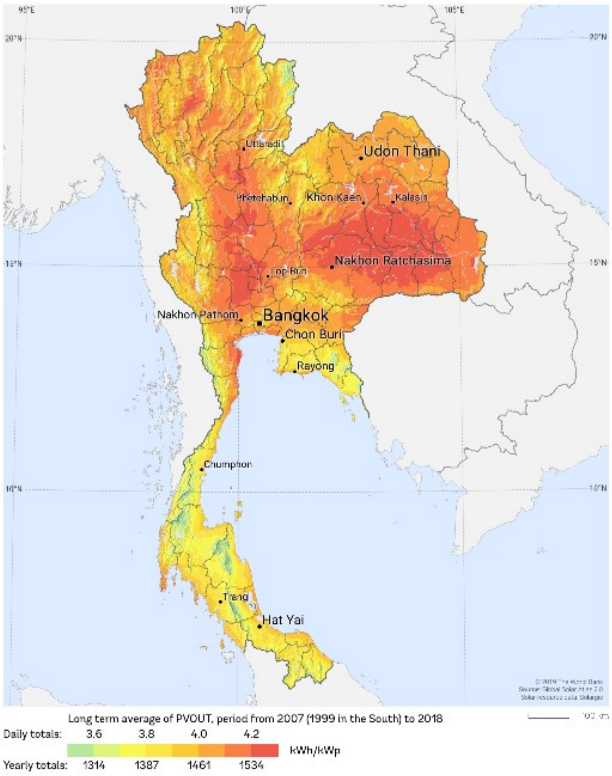

Fig. 3. Thailand photovoltaic potential map (Source of image : https://globalsolaratlas.info/download/thailand).

$$\mathrm{EN}_{AC} = \mathrm{PR} \times \left[P_{STC} \times \left(\frac{G_{POA}}{G_{STC}} \right) \right] \tag{8}$$

where EN_{AC} is the PV output, kWh; PR is the overall efficiency coefficient, 0.82 in this study; P_{STC} is the capacity of the installed PV system, 980 kW in this study; G_{POA} is local horizontal irradiance, kWh/m^2; G_{STC} is the standard test condition of PV, 1000 W/m^2.

The amount of NG consumption reduced by PV system (NR), NR is calculated as follows:

$$N_R = \mathrm{EN}_{AC} \times NHR_c \tag{9}$$

where N_R is the amount of natural gas consumption reduced by the PV system, kJ; NHR_C is the net heat rate of GTCC, kJ/kWh as per equation Eq. (7).

2.5. Internal Rate of Return and Payback Period

The IRR and PBP are widely used for economic evaluation of energy conservation investment project, so PV assisted GTCC is studied for finding the IRR, and PB. Formula and Calculation for IRR used to determine the figure are as follows:

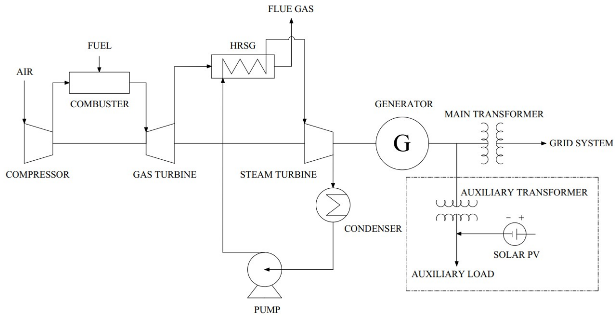

Fig. 4. Proposed solar PV to assisted GTCC.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{10}$$

C_t is net cash flow during the period t; C_0 is total investment costs; IRR is Internal Rate of Return; where t is number of time period [24, 25].

PBP simply computes how fast a project will recover its cash investment. A simple payback period is calculated as follows:

$$PBP = \frac{I}{P} \tag{11}$$

I is the investments; where P is annual savings [25].

3. Experimental setup

This study is an actual case study of the independent power producer's (IPP) 700 MW GTCC power plant in Thailand by installing solar rooftop PV (980 kW) for supplying the auxiliary equipment of the power plant and then comparing the heat rate of GTCC between the proposed method and conventional GTCC. The schematic of the proposed concept is shown in Fig. 4, and the real installed figure is shown in Fig. 5. The modification is to only tie in electricity from solar PV (rooftop solar) from each building in the power plant to the incoming bus of each building. Whenever solar PV supplies electricity to the incoming bus of a building equal to GTCC, it can reduce auxiliary power from itself.

The heat rate test and test conditions are according to the Mitsubishi performance test procedure [16] and ASME PTC 46 [17]. The calculated heat rate from testing is corrected back to the reference ambient condition in order to make the result comparable by using the GTCC manufacturer's correction curve. The heat rate test was set up on February 10, 2022, by using the data recorder of the power plant to record data. The test period is totally 2 hours for each test, with load stabilization taking 1 hour and data recording for heat rate calculation taking 1 hour. During

Fig. 5. GTCC power plant 700 MW which installed 980 kW solar PV.

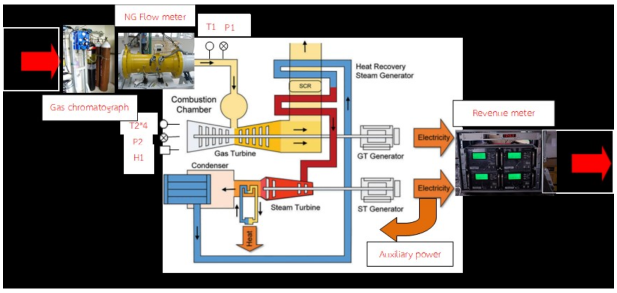

Fig. 6. Conventional GTCC which auxiliary power supply by GTCC.

the 2 hours of testing, GTCC MW output is controlled in local mode, separate from dispatch instructions from the national control center (NCC) of the Electricity Generating Authority of Thailand (EGAT). The operation condition of GTCC MW output during the test is set up to be maximum capacity rate (MCR) by selecting GT control mode to be exhaust gas temperature control in order to let GT raise MCR by controlling the firing temperature of GT. While steam turbines also generate maximum capacity from the highest exhaust temperature of GT, the total output of GTCC is MCR.

During the test, data is collected and recorded for GTCC heat rate calculation in 2 patterns are as follows.

1. Conventional GTCC which is normal feature of GTCC, the total auxiliary equipment of power plant receives total energy from GTCC itself as shown in the Fig. 6.

2. Proposed method which using solar PV 980 kW for supplying some portion of auxiliary equipment of the power plant as shown in the Fig. 7.

From the features of the testing circuit, there are three

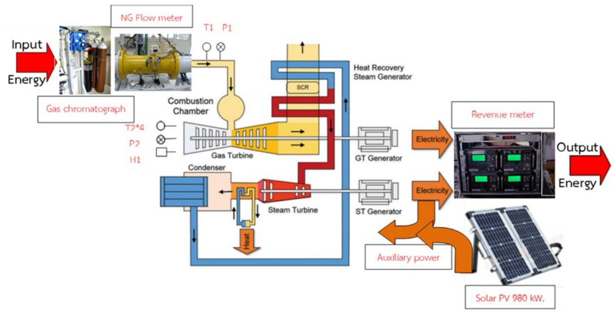

Fig. 7. Proposed method which using solar PV 980 kW for supplying auxiliary power.

important portions: input energy from fuel burned, output energy from electricity from the revenue meter, and ambient condition measurement for the elimination of uncontrollable conditions by using a correction curve. Hence, according to standard test conditions, the parameters controlled during the test are listed in Table 2. Therefore, if all of the test conditions and measurement parameters conform to the test code, we can ensure accuracy and reliable performance evaluation.

After testing, GTCC heat rate is calculated by using the recorded data from data recorder as per Eq. (1) to Eq. (7).

The economic evaluation of a PV-Assisted Combined Cycle Power Plant is extremely interesting for discussion from an economic point of view before making an investment. PV_{sys} instant software is used in this research to simulate electricity generation, and the actual total solar PV generation in the year 2022 was recorded by the data recorder of the power plant to compare and prove the accuracy of PV_{sys} instant software. The investment cost and operation and maintenance (O&M) cost are based on actual bidding data, and then the IRR and PBP are calculated according to Eqs. (10) and (11).

4. Result discussions

4.1. GTCC Heat rate comparison

After installed solar PV 980 kW to GTCC 700 MW, the heat rate test was performed on 10 February 2022 according to the test condition, the raw data and calculation result are shown as follow.

From Table 3, it can be seen that the corrected net heat rate of GTCC with solar is lower than conventional GTCC, equal to 59.17 kJ/kWh, or the heat rate is improved by 0.8%. At the test time, even though the power output of conventional GTCC was 739, 501 kW, which was higher than GTCC with Solar's 731, 436 kW, the energy consumed by conventional GTCC was also higher at 5,330 GJ compared to GTCC with Solar's 5,251 GJ. Furthermore, the

Table 2. Controlled Parameter during the test.

Variable	Permissible rapid fluctuation from the average test value during any one test run
Ambient Air Temperature	$+/-2.0°C$
Atmospheric Pressure	0.50%
Power output	2.0%
Fuel gas heating value	1.0%
Speed	1.0%

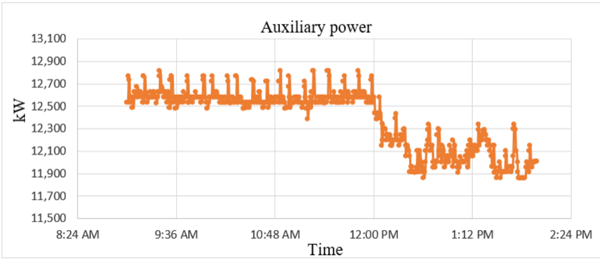

Fig. 8. auxiliary power consumption reduced when GTCC with solar was in operation in the afternoon.

uncontrollable impact of ambient conditions was taken out by correction factors such as the impact of ambient temperature, in the afternoon was 32.73°C hotter than in the morning (30.3°C); therefore, ambient temperature correction factors were 1.00106 and 0.99646 , respectively. The substantiated parameter that could be observed during the heat rate test was auxiliary power, which decreased when GTCC with solar was in operation in the afternoon. As shown in Figure 8, the auxiliary power generated from GTCC was reduced from 12,600 kW to around 12,000 kW.

4.2. Energy output from solar PV

The data was recorded to investigate the performance of a PV-assisted GTCC power plant. The main parameters of a 700 MW GTCC power plant located in the middle area of Thailand are shown in Table 4.

A PV system with a capacity of 980 kW was installed in the power plant; the actual output of the PV system was recorded and compared to the predicted output by PV_{sys} Instant software as per Eq. (8). Actual yearly PV system outputs and predicted PV output are nearly the same, with only a 2.69% difference, as shown in Table 5.

From Table 4, the average auxiliary energy consumption rate in the past 5 years was 2.76%, i.e., the annual energy output and auxiliary energy consumption were 3,218,147,020kWh and 86,521,660kWh, respectively. The PV system generates 1,393,379kWh of electricity annually, which is equal to 1.61% of average auxiliary energy consumption (the year 2017-2021) and makes the auxiliary energy consumption rate decrease from 2.76% to 2.72%. This reduction is not significant compared to total auxiliary consumption. The reason is that the installed capacity of the PV system is too small to cover auxiliary energy consumption. However, as the PV system is installed on the power plant with the existing facility, the cost of installation is low compared to the greenfield project. This feature will be important for the consideration of the solar PV system's capacity to assist the GTCC power plant.

4.3. Economic analysis

The cost of PV systems includes the initial capital investment cost for the PV system and the operating and maintenance (O&M) cost equal to 18.13 million THB, as shown in Table 6.

Due to the windy and dusty weather in Thailand, operation and maintenance (O&M) costs should be considered. The panels shall be cleaned three times a year, following the cleaningup requirements. With the local wage standard and management fees considered, the total annual O&M expenditure is estimated to be around 258,634 THB per year and 2,219,857 THB for the entire service period.

The Internal Rate of Return (IRR) and Payback Period (PBP) are calculated, and the results can be concluded in Table 7 based on NG prices of 473.36THB/MMBTU as per the Petroleum Authority of Thailand (PTT) billing of May 2022.

From Table 7, because this GTCC lifetime has 10 years remaining, the IRR is based on the 10-year assumption. As per the result, the IRR is 19.9%, in accordance with the PBP, which is the payback period of only 4 years and 2 months as well as the initial investment cost of 18.1 million THB. Although the electricity generation is too small to cover auxiliary energy consumption, the economic point of view is the most influential.

5. Conclusions

In this research, the concept of PV-assisted GTCC power plant technology was proposed, and a 700MW GTCC power plant in Thailand was selected as a case study to evaluate its performance. The results show that the GTCC heat rate was reduced by 59.17 kJ/kWh, or 0.8%, by using

Table 3. Heat rate calculation compare between conventional GTCC and GTCC with solar.

				Conventional GTCC		GTCC with solar	
Step-1	**Measure data for fuel gas flow calculation**	**Unit**	**Symbol**	**Test time 10.00-11.00**		**Test time 13.00-14.00**	
				GT21	**GT22**	**GT21**	**GT22**
1	Static pressure at flow condition	bar(g)	Pfa	35.18	35.11	35.47	35.40
2	Temperature at flow condition	°C	Tfg	27.24	27.43	27.69	27.82
4	Measure pulse flow at start of test	pulse	$Pulse_{start}$	9327664	5733060	173044	6573908
5	Measure pulse flow at stop of test	pulse	$Pulse_{stop}$	9612874	6016832	452352	6851522
6	K-factor of flow meter	pulse/m3	K-factor	118.55	118.82	118.55	118.82
7	Measure total fuel gas flow	m3/h	Vf	2405.82	2388.27	2356.04	2336.44
	$Vf=(Pulse_{start}-Pulse_{stop})/K\text{-factor}$						
8	Flow deviation from actual flow	%	delta Qcalb	0.01	0.01	0.01	0.01
9	Corrected total fuel gas flow	m3/h	Vfc				
	$Vfc=Vf*(100\text{-delta }Q_{calb})/100$			2,405.59	2,388.04	2,355.80	2,336.21
Step-2	**Calculation of fuel gas flow rate**						
	Wt=Qac*rb*(Pa/Pb)*(Tb/Ta)*(Zb/Za)						
10	Density at flow condition	kg/m3	ra	29.10	29.02	29.28	29.22
11	Density at base condition(ISO 6976:1995)	kg/m3	rb	0.81	0.81	0.81	0.81
12	Static pressure gas at flow conditions	Mpa(a)	Pa	3.62	3.61	3.65	3.64
13	Static pressure gas at base conditions	Mpa(a)	Pb	0.10	0.10	0.10	0.10
14	Absolute temperature of gas at flow conditions	K	Ta	300.39	300.58	300.84	300.97
15	Absolute temperature of gas at base conditions	K	Tb	288.15	288.15	288.15	288.15
16	Compressibility factor at flow condition(AGA8)	-	Za	0.95	0.95	0.95	0.95
17	Compressibility factor at base condition(AGA8)	-	Zb	1.00	1.00	1.00	1.00
18	Calculate fuel gas flow	kg/h	Vb	69,995.49	69,309.24	68,984.89	68,252.33
19	Calculate total fuel gas flow	kg/h	Vb	139,304.74		137,237.22	
Step-3	**Net heat rate calculation**						
	NHRm=Vb*HHV/Net output energy						
20	NG high heating value (ISO6976)	kJ/kg	HHV	38,262.00		38,262.00	
21	Total energy consumption	kJ	Input energy	5,330,077,822.71		5,250,970,450.26	
22	Measure power output (revenue meter)	kWh	Output energy	739,501.97		731,436.00	
23	Measure net heat rate	kJ/kWh	NHRm	7,207.66		7,178.99	
Step-4	**Correction factor**						
	NHRc=NHRm/(H1*H2*H3*H4*H5)						
24	Ambient temperature correction factor	°C	H1 (30.3/32.73)	0.99646		1.00106	
25	Atmospheric pressure correction factor	mbar	H2 (1009.8/1006.73)	1.00000		1.00008	
26	Relative humidity correction factor	%	H3 (59.18/49.51)	0.99922		0.99876	
27	Excess air filter pressure loss correction factor	mmAq	H4 (49.88/49.86)	1.00000		1.00000	
28	Excess exhaust duct pressure loss correction factor	mmAq	H5 (380.88/371.86)	1.00000		1.00000	
29	Corrected net heat rate	kJ/kWh	NHRc	7,238.85		7,179.68	

Table 4. GTCC parameter.

Parameters	Value	Unit
Capacity	700.00	MW
Heat Rate	7,239	kJ/kWh
Average Gross Generation (2017-2021)	3,218,147	MWh
Average Net Generation (2017-2021)	3,131,625	MWh
Average Auxiliary Energy Consumption rate (2017-2021)	2.76	%
Average Auxiliary Energy Consumption (2017-2021)	86,521.66	MWh

Table 5. Year 2022 monthly energy output of the PV system.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Predict output (kWh)	123,100	98,800	136,500	137,300	120,200	122,500	122,600	115,200	108,700	112,300	114,600	119,000	1,430,800
Actual output (kWh)	114,350	105,381	138,181	132,615	113,998	124,665	122,200	115,246	113,258	100,174	100,427	112,884	1,393,379
Difference (%)	-7.65	6.24	1.22	-3.53	-5.44	1.74	-0.33	0.04	4.02	-12.10	-14.11	-5.42	-2.69

Table 6. The initial capital investment cost of the PV system 980 kW.

Capital category	Cost (THB)
PV module	7,000,000
Inverters	1,364,000
Monitoring and control system	447,140
DC cable	988,932
AC cable	2,453,400
Grounding system	382,887
MDB and protection	1,492,400
Mounting structure	465,906
Race way	653,770
Walkway	504,800
Lifeline roof safety	151,000
Ladder	55,000
Civil work	294,500
Water cleaning	259,641
Manpower	956,611
Machine	230,000
Operation & Maintenance in first 2 years	133,712
License permit	300,000
Total	18,133,699

a PV system of 980 kW to supply the auxiliary system, and it can compensate for the auxiliary power consumption of 1,393,379kWh of electricity yearly. According to the GTCC power plant heat rate, there is 10,086,671MJ of natural gas consumption reduction annually, or 100,867GJ saved in 10 years of the remaining lifetime of a power plant by this method. The total net cost of the PV system (980 kW) is approximately 20.35 million THB, and the project IRR and PBP are 19.9% and 4 years and 2 months, respectively, demonstrating that the PV system is economically attractive. Anyway, the results of IRR and PBP were based on the NG price of 473.36 THB/MMBTU from the PTT billing of May 2022. If the NG price is going up, the IRR will be getting higher and the PBP will be shorter. On the other hand, if the NG price is going down, the IRR will be getting lower and the PBP will be longer.

Most importantly, the system recommended in this research can supply auxiliary power to the GTCC power plant either during GTCC in-service or during its shutdown condition, which is much more beneficial when compared with importing the energy from the grid system when GTCC is on shutdown. Besides, the solar-assisted GTCC power plant takes advantage of existing infrastructure, such as distribution systems and an internal grid, which reduces the difficulty of construction and investment. Integrating PV systems into the GTCC power plant makes full use of the space in power plants, so there is no land acquisition requirement.

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References

[1] *Share of electricity production from renewables, 2022*. 2023. URL: https://ourworldindata.org/grapher/share-electricity-renewables.

[2] M. Mehrpooya, M. Taromi, and B. Ghorbani, (2019) *"Thermo-economic assessment and retrofitting of an existing electrical power plant with solar energy under different operational modes and part load conditions"* **Energy Reports** *5*: 1137–1150. DOI: 10.1016/j.egyr.2019.07.014.

[3] M. Ameri and M. Mohammadzadeh, (2018) *"Thermodynamic, thermoeconomic and life cycle assessment of a novel integrated solar combined cycle (ISCC) power plant"* **Sustainable Energy Technologies and Assessments** *27*: 192–205.

[4] N. Abdelhafidi, İ. H. Yılmaz, and N. E. I. Bachari, (2020) *"An innovative dynamic model for an integrated solar combined cycle power plant under off-design conditions"* **Energy Conversion and Management** *220*: 113066. DOI: 10.1016/j.enconman.2020.113066.

[5] N. Zhang, G. Yu, C. Huang, L. Duan, H. Hou, E. Hu, Z. Ding, and J. Wang, (2020) *"Full-day dynamic characteristics analysis of a solar aided coal-fired power plant in fuel saving mode"* **Energy** *208*: 118424. DOI: 10.1016/j.energy.2020.118424.

[6] K. B. Kiran, M. Indira, R. Nagaraja, et al., (2021) *"Mathematical modeling and evaluation of performance characteristics of a hybrid solar PV and wind energy system"* **Journal of Applied Science and Engineering** *25*(4): 785–797. DOI: 10.6180/jase.202208_25(4).0014.

[7] M. Jiang, Y. Lv, T. Wang, Z. Sun, J. Liu, X. Yu, and J. Yan, (2019) *"Performance analysis of a photovoltaics aided coal-fired power plant"* **Energy Procedia** *158*: 1348–1353. DOI: 10.1016/j.egypro.2019.01.330.

[8] G. Khankari and S. Karmakar, (2018) *"Power generation from fluegas waste heat in a 500 MWe subcritical coal-fired thermal power plant using solar assisted Kalina Cycle System 11"* **Applied Thermal Engineering** *138*: 235–245. DOI: 10.1016/j.applthermaleng.2018.03.096.

[9] H. Nami, A. Anvari-Moghaddam, and A. Arabkoohsar, (2020) *"Thermodynamic, economic, and environmental analyses of a waste-fired trigeneration plant"* **Energies** *13*(10): 2476. DOI: 10.3390/en13102476.

Table 7. Summaries of IRR, PBP, investment cost and cashflow of solar PV 980 kW (million THB).

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	Total	IRR	PBP
Cash flow	−18.1	4.6	4.5	4.2	4.2	4.2	4.1	4.1	4.1	4.0	4.0	**23.9**	**19.9%**	**4Y2M**

[10] Electricity Generating Authority of Thailand. 2023. URL: https://www.egat.co.th..

[11] G. Şen, M. Nil, H. Mamur, H. Doğan, M. Karamolla, M. Karaçor, F. Kuyucuoğlu, N. Yörükeren, and M. R. A. Bhuiyan, (2018) *"The effect of ambient temperature on electric power generation in natural gas combined cycle power plant—A case study"* **Energy Reports *4***: 682–690. DOI: 10.1016/j.egyr.2018.10.009.

[12] M. Islam, M. Hasanuzzaman, A. Pandey, and N. Rahim. "Modern energy conversion technologies". In: *Energy for sustainable development*. Elsevier, 2020, 19–39.

[13] P. Breeze. *Gas-Turbine power generation*. Academic Press, 2016.

[14] T. K. Ibrahim, M. Rahman, and A. N. Abdalla, (2011) *"Gas turbine configuration for improving the performance of combined cycle power plant"* **Procedia engineering *15***: 4216–4223.

[15] J. W. Burnett and L. L. Kiesling, (2019) *"Power plant heat-rate efficiency as a regulatory mechanism: Implications for emission rates and levels"* **Energy Policy *134***: 110980. DOI: 10.1016/j.enpol.2019.110980.

[16] S. M. Kim, W. N. Yun, C. H. Jang, and S. I. Park, (2016) *"Plant Minimum Stable Load (Pmin) Test for Ilijan CCPP"* **KEPCO Journal on Electric Power and Energy** 2(1): 83–88.

[17] P. G. Deen, J. Gutierrez, T. B. Sullivan, and J. R. Friedman. "Comparison of ASME PTC-46 Performance Test Correction Factors as Estimated in a Project Proposal Phase to Those Determined During Project Implementation". In: *ASME Power Conference*. ***42738***. 2007, 713–726. DOI: 10.1115/POWER2007-22107.

[18] S. Pandey and R. Kumar, (2017) *"Analysis of auxiliary energy consumption in utility scale solar PV power plant"* **International Journal of Current Engineering and Technology *7***(5): 1728–1729.

[19] T. N. Raval and R. Patel, (2013) *"Optimization of auxiliary power consumption of combined cycle power plant"* **Procedia Engineering *51***: 751–757. DOI: 10.1016/j.proeng.2013.01.107.

[20] K. Mongkoldhumrongkul, (2023) *"Techno-economic analysis of photovoltaic rooftop system on car parking area in Rayong, Thailand"* **Energy Reports *9***: 202–212. DOI: 10.1016/j.egyr.2022.10.421.

[21] 2023. URL: https://globalsolaratlas.info/download/thailand.

[22] *Total solar energy capacity in Thailand from 2012 to 2022(in megawatts)*. 2023. URL: https://www.statista.com/statistics/1006141/thailand-total-solar-energy-capacity/.

[23] S. Kurtz, J. Newmiller, A. Kimber, R. Flottemesch, E. Riley, T. Dierauf, J. McKee, and P. Krishnani. *Analysis of photovoltaic system energy performance evaluation method*. Tech. rep. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.

[24] D. G. Dhavale and J. Sarkis, (2018) *"Stochastic internal rate of return on investments in sustainable assets generating carbon credits"* **Computers & Operations Research *89***: 324–336. DOI: 10.1016/j.cor.2017.02.014.

[25] A. Orioli and A. Di Gangi, (2017) *"Six-years-long effects of the Italian policies for photovoltaics on the grid parity of grid-connected photovoltaic systems installed in urban contexts"* **Energy *130***: 55–75. DOI: 10.1016/j.energy.2017.04.069.