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Performance Analysis of a Photovoltaic Aided Combined Cycle Power Plant

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Abstract

In this research, the integration of solar photovoltaics (PV) into the Gas Turbine Combine Cycle power plant (GTCC) was studied. The performance including economic analysis and environmental impact was conducted by a case study of an Independent Power Producer of 700 MW. GTCC power plant in Thailand. The methodology of performance test and calculation were according to the American Society of Mechanical Engineers, Performance Test Code 46 Overall Plant Performance (ASME PTC46) which took out the uncontrolled effect of environments by using manufacturer correction curves. The results indicated that the PV system could replace some part of auxiliary power consumption using renewable electricity to reduce internal power consumption and emission. In this case, by utilizing PV system of 980 KW the electrical power generation was 1,431 MWh per year which natural gas consumption and CO_2 emission could be reduced by 10,358,792MJ and 856.6 ton$_s$ per year respectively. Due to the feature of the integration into the power plant, PV electricity can supply to the power plant, either in operation or put on shutdown. The investment cost, operation, and maintenance (O&M) expenditure were feasible compared with PV power generation.

Keywords: *Combine cycle, Photovoltaics, Auxiliary power consumption, Emission*

1. Introduction

Energy is a crucial basic factor for human life and is important for economic and social development in Thailand. Energy demand was grown by 3-5% (www.egat.co.th) every year even though the Covid-19 pandemic made energy demand slow down but in the long term tendency energy demand is still growing up. 57.55% of electricity in Thailand was made from natural gas (www.egat.co.th) which is more than half is imported from foreign countries. Therefore, natural gas is a primary fuel for the power plant in Thailand, and the major power plant to uses natural gas is the Gas Turbine Combine Cycle power plant (GTCC); 51.52% or 8,262 MW (www.egat.co.th) of the total installed electrical capacity was from GTCC. Although GTCC is quite popular in Thailand, there are some rooms for improvement such as auxiliary power consumption could be reduced, and still found environmental pollution from the power plant stack.

Renewable power generation has been significantly increased to mitigate negative environmental impacts including climate change from fossil power generation. One of the obstacles to renewable power generation is the unreliability of its due to solar irradiation or wind velocity could not being controlled, system balancing challenges, and low generation flexibility. In 2018, Thailand Power Development Plan was issued; the emphasis objective was to balance and promote several sources of renewable energy approximately 14,754MW of electricity from solar energy was planned to install at the end of the plan year 2037 (Power Development Plan, 2020). The common solution to solve the problem is adding battery energy storage (Jorgenson et al., 2018) which the cost of it is extremely high resulting significant increase in electricity bills. Integrating solar energy into CCGT power plants has been widely investigated mostly based on solar thermal energy (Wang, et al., 2016). However, few studies are focusing on PV systems combined with conventional CCGT plants. Therefore, it is the interest of this paper to propose a new concept to integrate a PV system onsite of a CCGT power plant. The schematic of this concept is shown in Figure 1.

The benefits of this research:

1. The power generated by the assisted PV system can be consumed completely by an auxiliary machine in the power plant, which avoids transmission congestion problems in comparison with the stand-alone PV system.
2. The proposed solar PV hybrids for the CCGT power plant may reduce the natural gas combustion by integrating renewable solar energy, thus reducing the consumption rate of fossil fuels and corresponding greenhouse gas emissions.

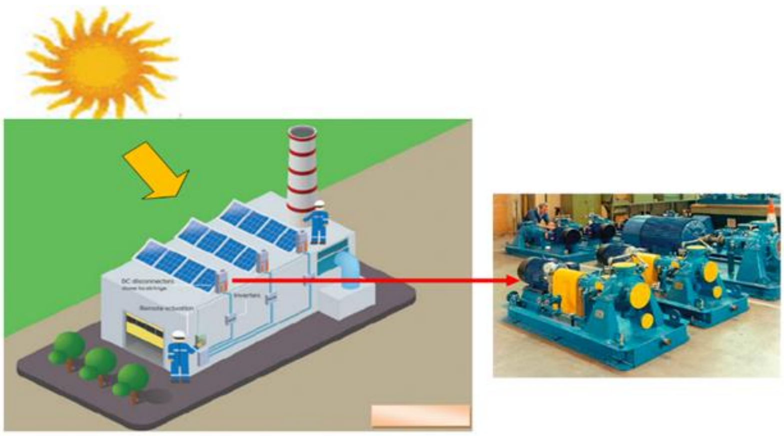

Figure 1: System sketch of PV aided combine cycle power plant

3. The hybrid solar-assisted CCGT power plant may take advantage of existing infrastructures, such as the distribution system and internal grid in the power plant, which reduces the difficulty of construction and investment.
4. Integrating the PV system into the CCGT power plant makes full use of the space in power plants, so there will be no land acquisition requirement.
5. No energy storage devices are required.

2. Methodology

2.1 PV system output

According to National Renewable Energy Laboratory (NREL) (National Renewable Energy Laboratory, 2013), PV output generation EN_{AC} is calculated as follows:

$$EN_{AC} = PR \times \left[P_{STC} \times \left(\frac{G_{POA}}{G_{STC}} \right) \right] \quad (1)$$

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,1000W/m^2.

2.2. Auxiliary power consumption of CCGT power plant

The amount of auxiliary power consumption of CCGT power plant E_{sc} was record from past 5 years, actual information as follows:

Table 1: Auxiliary energy from the past 5 years

Year	Gross generation (MWh)	Net generation (MWh)	Auxiliary Energy (MWh)	%
2021	1,803,933.34	1,749,903.74	54,029.60	**3.09**
2020	1,739,807.64	1,694,648.41	45,159.23	**2.66**
2019	3,768,098.81	3,672,319.38	95,779.43	**2.61**
2018	4,371,976.71	4,256,856.22	115,120.49	**2.70**
2017	4,406,918.62	4,284,399.09	122,519.53	**2.86**
Average	**3,218,147.02**	**3,131,625.37**	**86,521.66**	**2.76**

Therefore, the average auxiliary energy consumption was 86,521 MWh or 2.76% of net energy generation.

2.3. Contribution rate of PV system

The contribution rate of the PV system to CCGT power plant φ is calculated as follows:

$$\varphi = \frac{EN_{AC}}{E_{SC}}$$

Where φ is the contribution rate of the PV system to the CCGT power plant.

2.4. Natural gas consumption is reduced by the PV system

The amount of natural gas consumption reduced by PV system N_R is calculated as follows:

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$$N_R = EN_{AC} \times NHR_{CCGT}$$

Where N_R is the amount of natural gas consumption reduced by the PV system, kJ; NHR_{CCGT} is the net heat rate of CCGT, kJ/kWh. Calculated as follows:

$$NHR_{CCGT} = \frac{\text{Input Energy}}{\text{Net Output Energy}} \qquad)4($$

where Input Energy is the amount of heat from natural gas consumption supply to CCGT, kJ; Net Output Energy is electrical energy generated by CCGT, kWh (American Society of Mechanical Engineers, 2015).

2.5. CO_2 emission reduced by the PV system

The amount of CO_2 emission reduced by PV system E_{co2} is calculated as follows:

$$E_{co2} = EN_{AC} \times EF_{co2} \qquad)5($$

Where E_{CO2} is the amount of CO2 emission reduced by the PV system, kg_{CO2e}; EF_{CO2} is the emission factor of CO_2 per kWh, 0.5986 in this study (www.thaicarbonlabel.tgo.or.th).

3. Result

The simulation was carried out to investigate the performance of a PV-aided CCGT power plant. The main parameters of a 700 MW CCGT power plant located in the west area of Thailand are shown in Table 2.

Table 2: CCGT 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

A PV system with a capacity of 980 kW was installed in the power plant. According to Eq. 1 and the local solar radiation data from the PV Syst simulation, the output of the PV system can be predicted. Monthly PV system outputs are shown in Table 3.

Table 3: Monthly energy output of the PV system

	Predict	**Actual**	**Different**
Month	**Energy output (kWh)**	**Energy output (kWh)**	**%**
January	123,100	114,350	-7.65
February	98,800	105,381	6.25
March	136,500		
April	137,300		
May	120,200		
June	122,500		
July	122,600		
August	115,200		
September	108,700		
October	112,300		
November	114,600		
December	119,000		
Total	**1,430,800**		

3.1 Auxiliary energy consumption reduction effect

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 3,218,147,020 kWh and 86,521,660 kWh, respectively. The PV system generates 1,430,800 kWh electricity yearly is equal to 1.65% of total auxiliary energy consumption according to Eq. 2 and makes the auxiliary energy consumption rate decrease from 2.76% to 2.72%. This reduction is not significant compared to the 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. Hench a feature will be important for the consideration of the solar PV system's capacity to aid the CCGT power plant.

3.2 Advantage of reducing import energy from the grid system

The CCGT power plant was put on shutdown from time to time according to instruction from National Control Centre (NCC); during shutdown auxiliary power needed to be imported from the system grid and there was an electric tariff charge from the Electricity Generating Authority of Thailand (EGAT) as can be seen from graphic figure 2 below.

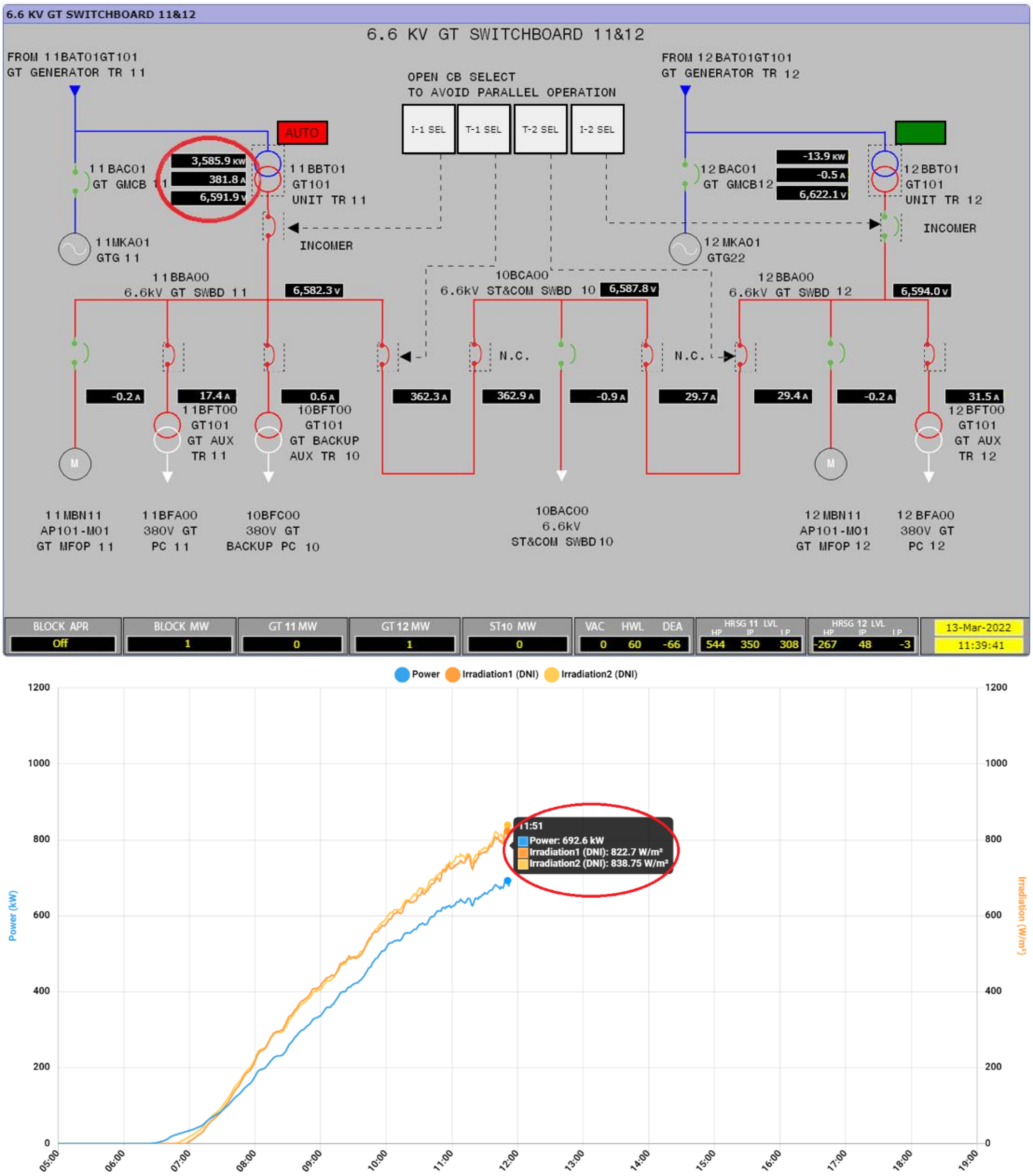

Figure 2: Import auxiliary power consumption during CCGT shutdown and solar system generation

Figure 2 was shown data of import auxiliary power during CCGT shutdown and solar power generation on 13 March 2022 time 11.31 hrs.; the data were 3,585.9 kW and 692.6 kW respectively. Without solar system generation, the import auxiliary power could be 4,278.5 kW instead of 3,585.9 kW at that time. The saving is subject to the hour of power plant shutdown, the more power plant put on shutdown, the more import auxiliary power saving by the solar system.

3.3 Environmental benefits

According to Eq.3 the net heat rate provided by the CCGT power plant was 7,239 kJ/kWh, so the PV system helps to save 10,358,792 MJ of natural gas yearly. According to Eq. 5 the PV system also helps to reduce 856 ton_e of CO_2 emission for the first year. For the entire service period, the system will reduce 103,587,920 MJ of natural gas consumption, and 8,560 tons of CO_2 emission due to there are 10 years remaining life of the power plant.

3.4 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. Table 4 summarizes the initial capital investment cost categories for the PV system.

Table 4: The initial capital investment cost of the PV system

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**

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

Moreover, one concern potential obstacle regarding the deployment of solar energy is its land use. Both photovoltaic power stations and solar thermal aided power stations to require additional land to deploy PV modules or solar collectors, leading to complicated land acquisition problems, administrative approval issues, and extra costs. Integrating PV systems within the

CCGT power plant area can make full use of the idle lands or roofs in the power plants, which avoids the issues and additional expenditure caused by land acquisition. Consequently, lower capital investment cost becomes a reality.

The total life-cycle cost of the PV system is 20.35 million THB. However, the system reduces the natural gas costs compared to a CCGT generation at about 41.53 million THB due to the reduced natural gas consumption of 98,187.6 MMBTU under the natural gas price of 422.93 THB/MMBTU.

4. Conclusion and Discussion

In this paper, the concept of PV aided CCGT power plant technology was proposed, and a 700 MW CCGT power plant in Thailand was selected as a case study to evaluate its performance. The results show that the PV system of 980 kW can compensate for the auxiliary power consumption of 1,430,800 kWh and reduce 856 ton_e of CO_2 emission annually. With the consideration of the benefit of reducing the natural gas consumption in a CCGT plant and 10 years of the remaining lifetime of a power plant, the total net cost of the PV system is approximately 20.35 million THB, which demonstrates the PV system is economically attractive. Most importantly, the system recommended in this paper can supply auxiliary power to the CCGT power plant either during CCGT in-service or shutdown conditions which is much more beneficial compared to importing energy from the grid system when CCGT is put on shutdown.

5. Acknowledgments

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