Proceedings of the 8th International Conference on Energy Harvesting, Storage, and Transfer (EHST 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 16-18, 2024
Paper No. 155
DOI: 10.11159/ehst24.155

Feasibility Assessment of Integrating Concentrating Solar Collectors with Gas Turbines in Low Direct Normal Irradiance Areas

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Abstract - The feasibility of integrating parabolic trough collectors (PTCs) with micro gas turbines (MGTs) in regions characterized by low Direct Normal Irradiance (DNI) was explored in this study. A transient simulation model was developed using MATLAB and typical meteorological year data to assess the impacts of varying DNI levels on the performance and efficiency of the system. The primary focus was on how the thermal efficiency of gas turbine cycles at different locations is influenced by the yearly average DNI. The findings revealed that by using the minimum annual average DNI difference as a reference, a reliable comparison and estimation of the gas turbine's thermal efficiency can be achieved. This approach confirmed a significant correlation between estimated and simulated thermal efficiencies, illustrating that the integration of PTCs with MGTs can substantially enhance system efficiency even in areas with low DNI. The robustness of this method highlights its potential as a predictive tool for optimizing the performance of hybrid solar-gas turbine systems across various geographical settings.

***Keywords*:** Concentrating Solar Collector, Gas Turbine, Thermal Energy Storage, Low DNI, Transient Simulation

1. Introduction

Renewable energy sources like solar energy have attracted significant attention for integration into diverse energy systems reducing reliance on fossil fuel consumption, despite their relatively high initial investment costs. Solar thermal technologies have been extensively studied and utilized in industrial and residential applications for many years [1]. Parabolic trough collectors (PTCs) and flat plate collectors are widely employed as concentrating and non-concentrating solar collectors these days.

The application of PTCs can be divided into two primary categories. The first category includes Concentrated Solar Power (CSP) plants, where the fluid temperature typically falls between 300°C and 400°C. The second category involves providing temperatures ranging from 100°C to 250°C for applications like domestic hot water supply, space heating, and heat-powered refrigeration, among other uses [2].

Solar energy has some drawbacks because it is instable and there is mismatch between energy supply and energy demand, more especially, during nighttime when there is not any solar radiation [3]. A viable remedy is the integration of a thermal energy storage (TES) unit into solar collectors to store excess heat and release it when it is required [4]. Sensible heat storage, latent heat storage and thermochemical storage are the main types of TESs systems [5].

Micro gas turbines (MGTs) represent a kind of gas turbine with power levels up to 500 kW. A typical MGT consists of a compressor, a combustion chamber, and a turbine. Modern high-efficient MGTs are commonly equipped with recuperators to recover waste heat [6]. Solar energy can be employed to enhance the efficiency of the MG cycles by preheating the compressed air to reduce the heat input to the system [1,7].

In this project, a 250 kW MGT cycle is integrated with a solar thermal collector system. A PTC absorbs available solar radiation to be stored in a TES, supplying the heat required to preheat the compressed air of the GT. As PTCs can only concentrate and utilize direct normal irradiance (DNI) [8], this work primarily focuses on the effect of DNI on the performance and efficiency of the proposed system. For this purpose, a transient model of the system is developed and simulated using MATLAB software, employing typical meteorological year (TMY) data from several locations with DNIs ranging from low to high. This simulation tests the feasibility of using such concentrating solar collectors in areas with low DNI. Besides, the minimum annual average DNI difference is used to estimate the yearly average thermal efficiency of GT cycles across different locations.

2. System Description and Assumptions

For this project, as depicted in Fig.1, a solar-assisted closed gas turbine cycle is considered in which a PTC absorbs DNI to enhance the temperature of the TES supplying the heat to reduce the heat input of the Brayton GT cycle. The closed GT cycles operate between two maximum and minimum temperatures with a certain pressure ratio, and the air exiting the compressor gains heat from the TES.

2.1. Assumptions

The main input data for the characteristics of the selected PTC are sourced from Ref [7]. Additional assumptions critical to this study are outlined as follows:

- PTCs are utilized as concentrating solar collectors and Syltherm 800 [9] is used as the heat transfer medium circulating within the solar collector system. The temperature of the oil should not exceed 600 degrees Celsius. One PTC is only employed to absorb DNI.
- The oil, with a heat capacity of 6,285 kJ/K, is used as a heat storage substance as well. At the start of the simulation, the oil in the fully insulated TES system is at 450 K.
- The air serves as the working fluid for the closed Brayton GT cycle under the air-standard assumption. It is assumed that the minimum and maximum temperatures of the GT are 300 K and 1300 K, and the pressure ratio for the GT equals 8, and the GT generates 250 kW net power output.
- Pinch point temperature difference (PPTD) between the oil in the TES and the air in the GT is maintained at 5 K.
- When the DNI equals zero, oil does not circulate within the collector, not supplying any heat transfer from the collectors to the TES. Thermal energy from the storage can only be utilized by the GT plant's air if the temperature difference between the TES and the outlet state of the compressor exceeds PPTD.

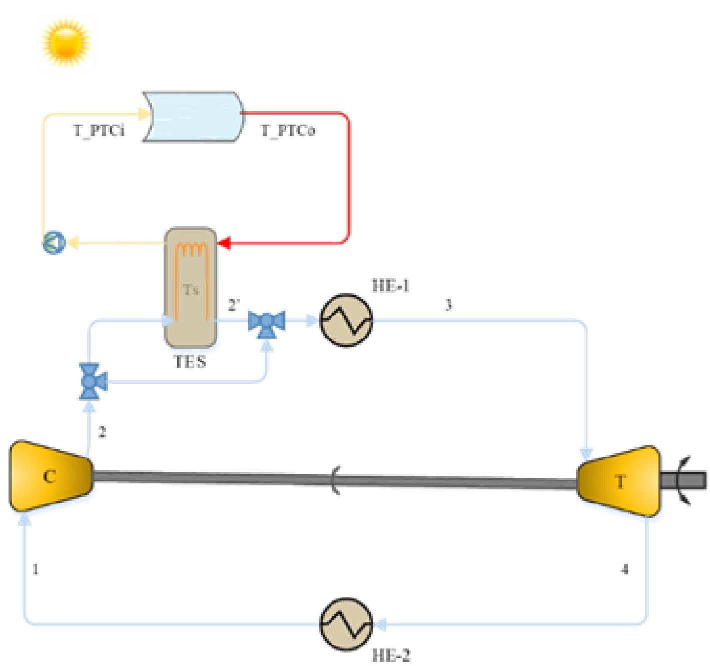

Fig. 1: Schematic representation of the proposed system.

3. Modelling

In this section, the main correlations for modeling the PTC, TES, and GT are represented. More details can be found in in the corresponding references [7, 8]. The useful energy rate of the PTC ($\dot{Q}_u$), the temperature of the storage tank at the next next time step (T_s^+), and thermal efficiency of the GT (η_{GT}) can be expresses in Eq. (1), (2) and (3), respectively. The details details of parameters and subscripts/superscripts used are defined in the nomenclature.

$$\dot{Q}_u = A_{ap} \cdot F_R \cdot \left(S - A_{rec}/A_{ap} \cdot U_L \cdot \left(T_{Oil,i} - T_a\right)\right) = \dot{m}_{Oil} \cdot (h_{Oil,o} - h_{Oil,i}) \tag{1}$$

$$T_s^+ = T_s + \frac{\Delta t}{\left(mC_p\right)_s}\left[\dot{Q}_u - \dot{L}_s - (UA)_s(T_s - T_a')\right] \tag{2}$$

$$\eta_{GT} = \frac{w_{net}}{q_{in}} \tag{3}$$

4. Validation

Fig.2 depicts the comparison between the results of the present model in MATLAB for a single PTC and the analytical and experimental results represented by Dudley et.al [10]. Black chrome material case for a vacuum space between the receiver and its cover is used for this modelling and Sytherm-800 oil is employed as the working fluid flowing within the receiver pipe. This figure versifies the accuracy of the present model as there is good agreement between the results.

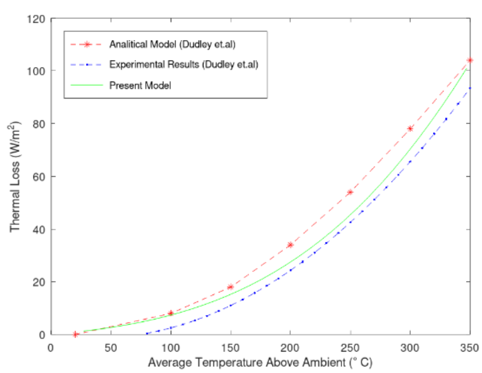

Fig. 2: Validatio of the present model with the results represented by Dudley et.al.[10].

5. Results and Discussion

In this section, several parameters will first be assessed for Toronto, which experiences relatively low Direct Normal Irradiance (DNI). These parameters include the inlet and outlet temperatures of the oil flowing through the PTC (T_{PTCi} and T_{PTCo}, respectively), direct normal irradiance (DNI), temperature of the storage tank (T_s), and thermal efficiency of the micro gas turbine plant (η_{GT}). This case study is divided into two distinct schemes. The first scheme analyzes the variations in the selected output parameters on a specific day, namely January 4th. The second scheme evaluates the yearly changes in these parameters. Furthermore, the impact of the yearly average DNI on the yearly average thermal efficiency across twelve different cities will be analyzed.

5.1. Case Study

The short-term operational efficacy of the solar thermal system with PTCs integrated into a gas turbine system on a typical winter day in Toronto when solar irradiance is at one of its lowest points will be assessed in the following.

For this day, DNI is available for only 8 hours from 8:30 to 15:30, with an average value of 224.21 W/m^2 (represented by a dashed-dotted line). As illustrated in Fig.3, oil starts circulating within the concentrators at 8:30, when DNI first becomes greater than zero. This circulation increases the temperature of both the oil and the TES. Once the last DNI greater than zero is recorded, the oil's temperature ceases to rise, and no further energy is added to the TES.

Because T_s meets the PPTD criterion, the air can be heated by the thermal energy from the oil from the start to the end of the day. Consequently, the temperature of the thermal energy storage slightly declines overnight when there is no DNI, but it increases during the day as it absorbs solar energy through the concentrating solar collectors.

As a result of utilizing thermal energy from the storage tank throughout the day, the thermal efficiency of the GT exceeds the typical operation rate of 44.80%. Since there is no DNI during the first 8 hours of the day, the efficiency slightly decreases until the solar collectors absorb the first DNI, which then benefits the TES and GT.

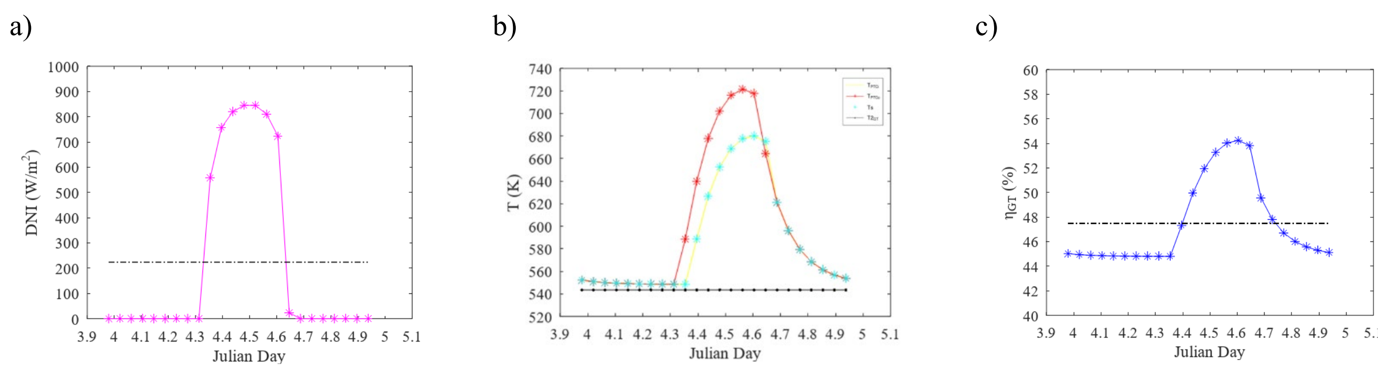

Fig. 3: Hourly and average values of a) DNI, b) T_{PTCi}, T_{PTCo},$T2_{GT}$ T_s, and c) η_{GT}.

Fig.4 illustrates the yearly transient behavior of the selected output parameters including DNI, T_s, and η_{GT} along with their average values. In Toronto, with an average DNI of 168.10 W/m², the average temperature of the thermal storage and the average thermal efficiency reach 571.33 K and 46.72%, respectively. This figure indicates that the system's behavior is highly reliance on the change in the DNI amount. For example, during the last 50 days of the year when the DNI values are at their lowest (Fig.4.a,), less thermal energy can be stored in the TES (Fig.4.b) and utilized by the GT to enhance its efficiency (Fig.4.c). It should be noted that dashed-dotted lines represent the annual average values.

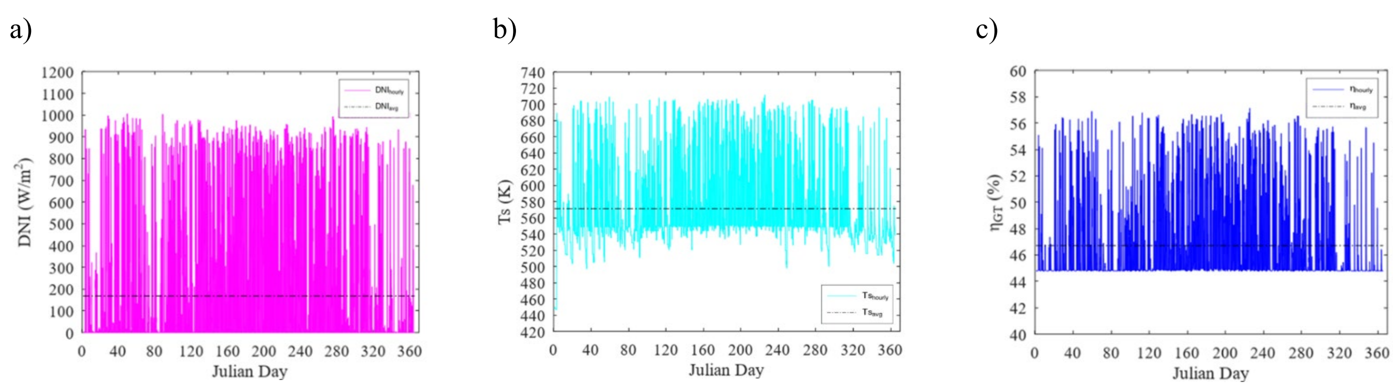

Fig. 4: Yearly and annual average values of a) DNI, b) T_s, and c) η_{GT}.

5.2. Different Locations

In the following, the effect of location with yearly average DNI is analyzed. For this, six cities in Canada and six cities in Iran are considered. According to the evaluation results depicted in Fig.5, the annual average thermal efficiency of the GT depends highly on the annual average DNI of the location; as the average DNI increases, more thermal energy is available, capable of supplementing further solar heat input to the GT cycle to reduce the input external heat.

The solar-assisted system in Yazd, which has the highest average DNI (264.51 W/m²), can increase the average efficiency of the system by 3.14% (from 44.80% to 47.94%). Conversely, Rasht, with the lowest DNI (135.36 W/m²), contributes to only a 1.51% increase in the thermal efficiency.

a) b)

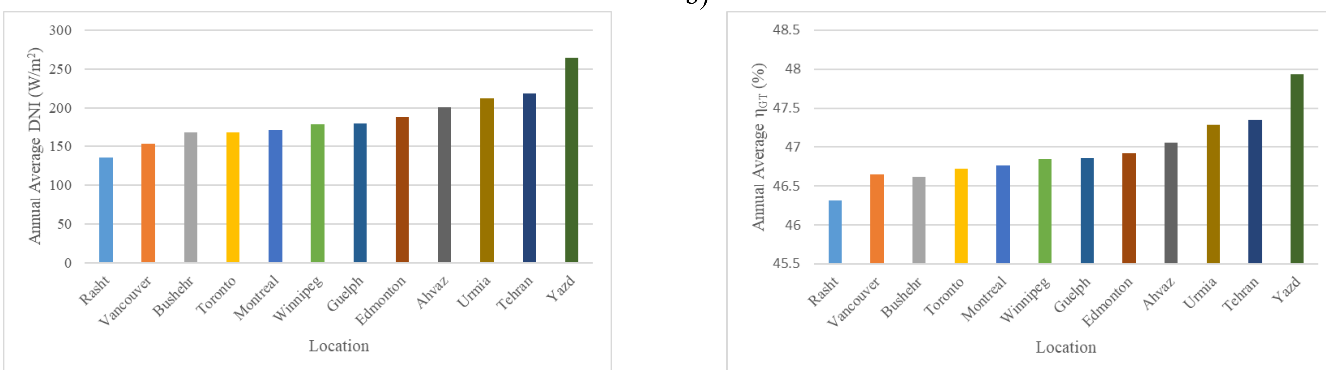

Fig. 5: Effect of location on the a) annual average DNI and b) annual average thermal efficiency.

The yearly average estimated thermal efficiency (η_{avg}^{est}) of a gas turbine for a particular location is determined by comparing the yearly average DNI difference with other cities. The city with the least DNI difference is selected as the reference point for the estimation. This estimated efficiency is then compared with the calculated efficiency (η_{avg}^{cal}) derived from simulation data. For instance, Vancouver is identified as the city most comparable to Rasht in terms of average DNI, which has a thermal efficiency of 46.65%. The discrepancy between this value and the actual efficiency of Rasht (46.31%) is 0.72%. Table 1 presents both the simulated and estimated thermal efficiencies of gas turbines for the locations considered.

Table 1: Simulated and estimated thermal efficiencies of the GT for the locations.

Location	DNI_{avg} (W/m²)	ΔDNI_{avg}^{min} (W/m²)		η_{avg}^{sim} (%)	η_{avg}^{est} (%)	$error$ (%)
		Value	**Location**			
Rasht	135.36	18.24	Vancouver	46.31	46.65	0.72
Vancouver	153.60	14.14	Bushehr	46.65	46.62	0.06
Bushehr	167.74	0.36	Toronto	46.62	46.72	0.20
Toronto	168.10	0.36	Bushehr	46.72	46.62	0.20
Montreal	171.28	3.19	Toronto	46.77	46.72	0.11
Winnipeg	178.51	0.88	Guelph	46.85	46.86	0.03
Guelph	179.39	0.88	Winnipeg	46.86	46.85	0.03
Edmonton	187.69	8.30	Guelph	46.92	46.85	0.15
Ahvaz	200.48	11.32	Urmia	47.06	47.29	0.48
Urmia	211.80	6.96	Tehran	47.29	47.35	0.13
Tehran	218.76	6.96	Urmia	47.35	47.29	0.13
Yazd	264.51	45.76	Tehran	47.94	47.35	1.24

6. Conclusion

This study conducted on integrating concentrating solar thermal collectors with a micro gas turbine highlights the significant dependency of thermal system performance on DNI. The analysis indicates:

- The operational efficacy of the system fluctuates daily and seasonally with DNI levels. On January 4th, a typical winter day with low solar irradiance, the system managed to maintain functional thermal efficiency due to the heat stored from previous operations. This was evident from the gradual increase in the oil and thermal storage tank temperatures whenever the DNI was available (8:30 to 15:30), enhancing the GT's performance.
- Throughout the year, particularly during the last 50 days when the DNI is at its lowest, the system's ability to store and utilize thermal energy significantly diminishes for Toronto. However, the yearly average figures suggest a thermal efficiency of 46.72% for the GT, which is an improvement over typical operations, attributable to the strategic use of stored thermal energy.
- The comparison across twelve different locations with varying average DNI levels revealed a clear correlation between DNI and thermal efficiency of the GT system. Yazd, with the highest DNI, showed a potential efficiency increase up to 47.94%, whereas Rasht, with the lowest DNI, showed a minimal increase to 46.31%.
- Employing the smallest annual average DNI difference, the calculated annual average thermal efficiency of the GT across all locations demonstrates a strong correlation between the estimated values and those obtained from simulations.

The integration of PTC with MGTs employing TESs, especially in areas with low DNI, presents a viable solution to enhance the overall efficiency of thermal power systems. This approach not only maximizes the use of available solar energy but also stabilizes the energy supply by mitigating the variability in solar resources. By utilizing the minimum annual average DNI difference as a basis for comparison, this study has established a robust correlation between the estimated and simulated annual average thermal efficiencies for GT cycles across various locations. This finding underscores the reliability of the employed methodology for predicting GT performance based on DNI variances.

Nomenclature

A_{ap}	aperture area, m^2	MGT	micro gas turbine	**Superscripts/ Subscripts**	
A_{rec}	receiver area. m^2	PTC	parabolic trough collector	a	ambient
C	compressor	q	heat transfer amount J	avg	average
Cp	isobaric specific heat, J/kg-K	$\dot{Q}$	heat transfer rate, W	est	estimated
CSP	concentrated solar power	S	radiation absorbed by receiver, W/m^2	i	inlet
DNI	direct normal irradiance, W/m^2	T	temperature, K	in	input
F_R	heat removal factor	T	turbine	min	minimum
GT	gas turbine	TES	thermal energy storage	o	outlet
h	specific enthalpy, J/kg	U_L	overall heat loss coefficient of the solar collector, W/m^2-K	rec	receiver
HE	heat exchanger	w	net output work, J	s	storage
$\dot{L}$	load rate, W	**Greek Letters**		sim	simulated
m	mass, kg	Δ	difference	.	rate of a component
$\dot{m}$	mass flow rate, kg/s	η	thermal efficiency	$'$	next to the device

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