Enhancing the Efficiency of a Gas Turbine Through the Integration of Solar Heat - a Case Study of Tashkent CHP

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Abstract: Solar power is currently a widely recognized energy source that has gained significant attention from numerous countries. Over time, two predominant solar technologies have emerged internationally: solar photovoltaics and solar thermal power. In the case of solar photovoltaics, sunlight is directly converted into electricity. However, despite advancements in thin-film solar photovoltaics, they still exhibit lower electricity output due to the uncontrollable and highly variable nature of rapidly changing weather conditions. Solar thermal power, on the other hand, harnesses solar heat in power plants to generate electricity. However, this type of power generation faces similar challenges. The lack of high-capacity thermal storage contributes to its inherent unpredictability and variability. In the coming years, the solar thermal power industry in Uzbekistan should prioritize harnessing the unique advantages offered by the combination of hybridization and thermal energy storage. With decreasing costs and the increasing adoption of renewable energies, solar thermal power plants have the capability to provide dispatchable power, making them highly suitable for a pivotal role in a future energy grid primarily powered by renewable sources.

1 INTRODUCTION

In Uzbekistan, the energy system has experienced stagnation over nearly a quarter of a century, with existing heat and electricity generating facilities constructed in the 1960s and 1980s struggling to meet the escalating demands of a growing population and expanding industrial sector. Consequently, the country has faced significant energy crises. Recent efforts have been undertaken to address this challenge, marked by decisions from the authority [1], including the establishment of a dedicated Ministry of Energy. This ministry represents the singular entity within the fuel and energy sector specifically tasked with ensuring the energy security of Uzbekistan, facilitating a stable supply of fuel and energy resources to economic sectors and the population, and advancing the promotion and development of renewable energy sources [2]. Notably, considerable emphasis has been placed on the construction of contemporary steam-gas stations, marking a departure from antiquated Rankine cycle devices characterized by low efficiency. However, it is imperative to acknowledge certain drawbacks associated with the adoption of steam-gas devices:

- High Fuel Consumption: Gas turbines, a key component of power plants, are acknowledged for their elevated fuel consumption. This characteristic poses the risk of increased operational costs and adverse environmental impacts.
- Low Part-Load Efficiency: A notable limitation of gas turbines is their diminished efficiency when operating at less than maximum capacity, commonly referred to as part-load conditions [3].

A potential solution to address these challenges involves the integration of solar power technology with the existing power plant infrastructure, which could result in improved efficiency and reduced fuel consumption.

2 STATE OF THE ART OF THE PROBLEM

In recent years, the utilization of gas turbines has experienced significant growth in industries such as petrochemicals, power generation, and offshore operations. The power sector, in particular, has witnessed a surge in the adoption of combined cycle power plants, with the latest high-efficiency gas turbines playing a pivotal role in this expansion.

The increasing costs associated with natural gas have posed challenges for gas turbine plants originally designed for continuous base load operation. Many of these plants are now operating at varying loads, ranging from 50% to full load, and in some cases, they have to be shut down on weekends. The latest maintenance guidelines, including case studies, aim to support engineers working in the field who must operate these plants under non-ideal conditions that deviate from their original design parameters of base-loaded operation. Currently, numerous alternatives have been devised with a specific focus on reducing fuel consumption. Specifically, the integration of solar power into existing gas turbines is developing rapidly, and research is underway on many small-scale Solar Hybrid Gas Turbines (SHGT).

The outcomes of investigations in the realm of gas turbine hybridization have been announced by numerous researchers, accompanied by several authors reporting the findings of case studies focused on enhancing gas turbine performance through the utilization of solar power.

Faustino Moreno-Gamboa et al [3]. extensively documented the performance of an externally fired hybrid solar gas-turbine power plant in Colombia. Their study employed energy and exergy methods, taking into account local environmental conditions, such as ambient temperature and solar resource availability, as well as plant models and thermodynamic properties of the working fluid, utilizing the Modelica compiler Dymola. The results obtained from their investigation revealed that the efficiency of a solar concentration system is relatively less affected by solar radiation variations occurring around noon. However, the impact becomes more pronounced during sunrise and sunset periods. Notably, an escalation in radiation levels leads to heightened exergy destruction in both the heliostats field and the solar receiver, thereby causing a decline in the overall exergetic efficiency of the entire plant. Moreover, the effectiveness of the heat exchangers within the combustion chamber and the subsequent dissipation of heat into the environment have a direct and consequential influence on the performance of the hybrid solar plant. A decrease in the efficiency of these heat exchangers further exacerbates the detrimental effects, impairing the plant's overall functionality and efficiency.

The study conducted by Guzman [4] provides valuable insights into the operational characteristics and optimization potential of the parabolic trough solar power plant in Barranquilla. By employing the SAM, a widely recognized tool for analyzing renewable energy systems, the study contributes to the academic understanding of solar power plant performance in the specific geographical context of Barranquilla. The results underscore the plant's ability to generate substantial electricity output throughout the year, with May emerging as the peak production month. Moreover, the efficient utilization of solar radiation during peak periods obviates the requirement for supplementary stored energy, further enhancing the plant's operational efficiency and economic viability.

T. Prosin et al [5]. conducted an investigation on the initial modeling results of a centrifugal receiver system, specifically focusing on a turbine with a power output of 100 kW and a more efficient 4.6 MW unit. The study concludes that the payback time for the 100 kW microturbine is significantly low, indicating its economic feasibility. Moreover, the 4.6 MW unit demonstrates considerable potential and represents a promising market opportunity.

A study by Wujun Wang et al [6]. demonstrated the capabilities of load flexible combustors for hybrid Brayton applications. Using the KTH high flux solar simulator, the researchers experimentally investigated combustor performance at 30% workload. To test behavior under varying conditions, they abruptly halted the solar simulator and simultaneously increased fuel injection. This enabled thorough examination of the combustor's performance. Despite terminating solar input, the results showed that manually adjusting the main fuel injection, maintained air outlet temperatures within 914.5± 10 °C, preventing flashback. Overall, by demonstrating stable outlet temperatures even when solar input was suddenly lost and fuel supply increased, the study successfully showcased the load flexibility of the combustor for hybrid Brayton systems across challenging operational scenarios.

However, more appealing papers are shortly described below.

P. Klein et al [7]. conducted an experimental test program to obtain high-temperature heat transfer data for a packed bed operating within two temperature ranges: 350-900 °C and 600-900 °C. The researchers utilized flue gas from a 45kW LPG burner to heat a packed bed of Denstone ceramic pebbles. To achieve the desired temperature ranges, the system was preheated before testing. The study involved measuring fluid and solid temperature profiles in the packed bed along both axial and radial dimensions. These measurements were then compared to a numerical model, showing a reasonable level of agreement. Additionally, the paper discusses potential modifications to the test facility and outlines plans for future testing.

R. Uhlig et al [8]. carried out an investigation to enhance the efficiency of Solar Hybrid Gas Turbine (SHGT) cavity receivers. The paper aimed to compare two different approaches to improve the receiver efficiency of a cavity receiver used in heating compressed air for a 4.7 MWel turbine. The desired temperature range was between 330°C and 800°C, with a mass flow rate of 15.9 kg/s at an absolute pressure of 10 bar. The researchers also analyzed the influence of various receiver sizes and explored a design option that involved incorporating a transparent covering for the aperture. The objective of this design option was to reduce convection losses. Furthermore, the study considered the impact of these enhancements on the levelized cost of energy (LCOE). The thermal and hydraulic layout was meticulously planned, accounting for a thermal heat input of 8.4 MWth and a 250 mbar pressure drop. Thermal finite element (FE) models were utilized for this purpose. These models took into consideration the local heat flux distribution, heat transfer to the working fluid, radiation exchange between components and the surrounding environment, as well as conduction and convection losses within the cavity.

The paper presents the groundbreaking Solugas project [9], which marks the introduction of a megawatt-scale solar hybrid gas turbine system. This innovative system combines a solar tower plant with a customized Mercury 50 gas turbine. At the heart of the system is the solar receiver, comprising 170 tubes crafted from nickel alloy. These tubes efficiently heat pressurized air to an impressive 800°C. The total solar input power generated by this setup amounts to approximately 7 MWth. Integration of the modified gas turbine with the solar receiver results in a net power output of 4.6 MWe. This remarkable achievement signifies the first-ever successful demonstration of solar hybrid gas turbine technology operating at a multi-megawatt capacity. The Solugas project serves as a testament to the technical feasibility and potential of solar hybrid gas turbines in generating cost-effective and dispatchable renewable power. The success of this project opens up exciting prospects for further capacity scaling in the future. With its maximum power output of 4.6 MWe, the Solugas project represents a significant milestone in the advancement of solar hybrid gas turbine technology. It showcases the successful construction and testing of a cutting-edge system that paves the way for a cleaner and more sustainable energy future.

Despite the numerous results announced in the field of solar hybrid micro gas turbines, in this paper, we investigate the possibilities of integrating solar energy into the larger MW-scale Tashkent CHP gas turbine.

3 MODELLING OF GOVERNING EQUATIONS

3.1 Gas Turbine CHP Thermodynamic Model

To assess the electrical efficiency of a gas turbine, it's essential to take into account the various components of the turbine. Specifically, we need to calculate the actual work done by the gas turbine compressor.

This work calculation is represented in Figure 1.

3.1.1 Calculating Electrical Efficiency

Assuming that the compressor adiabatic thermal efficiency is η_c [10].

$$W_{ca}=\frac{m_a(h_2-h_1)}{\eta_c},$$

where: m_a – mass flow of air (kg/s); h_1 – enthalpy of air at compressor inlet (kJ/kg); h_2 – air enthalpy at compressor outlet (kJ/kg).

Actual generated work of turbine is determined by equation [12]:

$$W_{ta} = (m_a + m_f)(h_3 - h_4)\eta_t,$$

where: m_f – mass flow of fuel (kg/s); h_3 – enthalpy at gas turbine inlet; h_4 – enthalpy at gas turbine outlet.

Thus, actual total work is:

$$W_{act} = W_{ta} - W_{ca}.$$

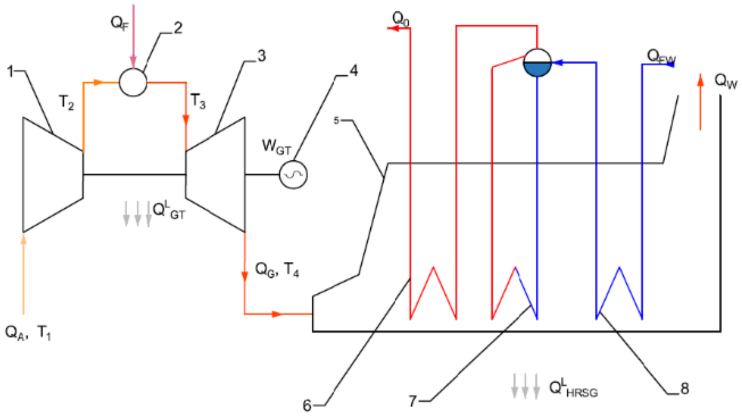
The overall internal efficiency of a gas turbine can be assessed using a specific equation:

$$\eta_c = \frac{W_{act}}{Q_F} = \frac{W_{act}}{m_f(LHV)},$$

where m_f – fuel mass flow to raise temperature and it is calculated by following equation:

$$m_f = \frac{h_3 - h_2}{(LHV)\eta_b},$$

where $h3$ – enthalpy at gas turbine inlet (kJ/kg).



1 – Compressor;
2 – Combustion chamber;
3 – Gas turbine;
4 – Generator
5 – HRSG;
6 – Superheater;
7 – Evaporating surfaces;
8 – Economizer;
W_{GT} – Gas turbine power output;
Q_A –Ambient air heat;
Q_F – Heat input into the gas turbine;
Q_{LGT} – Gas turbine heat losses;
Q_{GT} – Gas turbine waste gases heat;
Q_0 – HRSG steam heat;
Q_{FW} – Feed water heat;
Q_{LHRSG} – HRSG heat losses;
Q_W – HRSG waste gases heat.

Figure 1: Energy flow diagram of the gas turbine CHP without supplementary firing.

3.1.2 Heat Recovery Steam Generator

The heat output of the Heat Recovery Steam Generator (HRSG), which represents the heat absorbed by the water and steam within the HRSG, is calculated as follows:

$$Q_{HRSG}=Q_0-Q_{FW.}$$

It also possible to determine the heat output of the HRSG by equation:

$$Q_{HRSG}=M_{GT}(I_{GT}-I_w)=D_0(h_0-h_{fw}),$$

where: M_{GT} – the waste gases mass flow through turbine (kg/s); I_{GT} – gas turbine outlet enthalpy (kJ/kg); I_W – enthalpy of HRSG waste gases (kJ/kg); D_0 – H_{RSG} steam mass flow (kg/s); h_0 – H_{RSG} superheated steam enthalpy (kJ/kg); h_{fw} – H_{RSG} feed water enthalpy (kJ/kg).

The equation that defines the enthalpy of waste gases entering the evaporating surfaces at the inlet, denoted as IE, can be rephrased as follows:

$$I_E = c_{p.g} \times (t_s + \partial t_E),$$

where: t_s – saturated steam temperature in appropriate temperature; ∂t_E- Temperature difference between waste gasses and water evaporating surface inlet (°C).

The HRSG mass flow is defined by equation:

$$D_0 = \frac{\mathrm{G_{GT}} \times (\mathrm{I_{GT}} - \mathrm{I_E})}{(\mathrm{h_0} - \mathrm{h_E})}.$$

Heat balance equation for economizer:

$$G_{GT}\times(I_E-I_W)=D_0(h_0-h_{FW}).$$

It is possible to define the HRSG waste gasses temperature:

$$t_W = t_E - \frac{D_0(h_E - h_{FW})}{c_{p.g}G_{GT}}.$$

where t_E - The waste gasses temperature at evaporating surface inlet (°C).

Waste gasses temperature at evaporating surfaces inlet t_E is defined according to the enthalpy IE.
Now it is possible to define HRSG efficiency (utilization coefficient):

$$\eta_E = \frac{Q_{HRSG}}{G_H^E \times LHV}.$$

3.2 Gas Turbine with Solar Tower

To combine gas turbine and solar tower technologies for a hybrid solar power plant, Figure 2 illustrates the layout typically employed for utility-scale installations. Given the substantial power block size, the gas turbine must be located at the tower's base. Consequently, it becomes essential to transport the hot gases up and down the central tower, which introduces additional constraints related to temperature. To harness the sun's energy at elevated temperatures, it is necessary to employ high concentration ratios. These ratios help minimize radiation losses and ensure that the receiver maintains an acceptable level of efficiency.

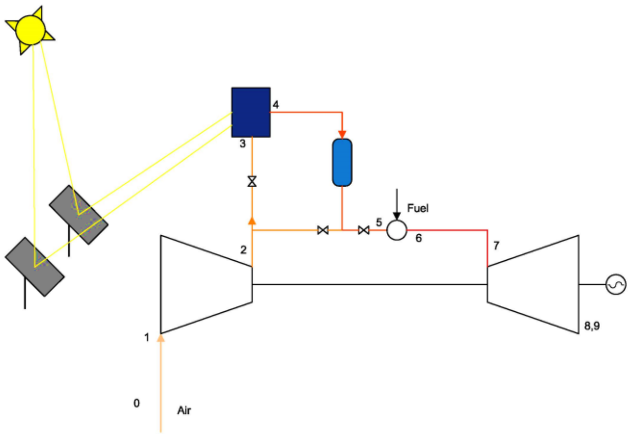


Figure 2: Schematic diagram of the simple-cycle hybrid solar gas-turbine: 1 – heliostats; 2 -solar receiver; 3- heat storage.

The amount of high-pressure compressor air diverted for cooling turbine blades and other purposes depends on the temperature at the combustion chamber's outlet. The hotter the combustion gases, the greater the volume of air needed for cooling. Some additional air is also taken for purging and sealing to prevent high-temperature gases from reaching unwanted areas. The remaining compressor airflow is directed to the solar subsystem, where it passes through the central tower's piping. Afterward, the preheated air from the solar receiver is sent to the combustion chamber, where a specific quantity of fuel is injected and burned to achieve the desired firing temperature. Solar preheating of compressor air significantly reduces fuel consumption, and adjustments to the combustion chamber's fuel flow can be easily and rapidly made to compensate for fluctuations in solar heat input, ensuring stable operation.

The extent of solar integration within a hybrid solar power system can be quantified using the solar share, denoted as f_{sol}. This parameter is defined in following equation as the ratio of the solar heat input (Q_{sol}) to the total heat input (Q_{tot}) for the entire cycle:

$$f_{sol} = \frac{Q^{+}_{sol}}{Q^{+}_{tot}}$$

The nominal solar share of a hybrid solar gas-turbine system is directly linked to key cycle temperatures, particularly the nominal receiver temperature (T_4) and the combustor outlet temperature (T_6). When the receiver temperature approaches the combustor outlet temperature, the solar share increases because less heat needs to be supplied through combustion. In the extreme case where T_4 equals T_6, the nominal solar share reaches 100%, and there is no need to burn any fuel. Neglecting losses in the tower piping, you can estimate the nominal solar share using (1), with T_5 representing the compressor discharge temperature and T_3 the receiver inlet temperature.

$$f_{sol,nom} \cong \frac{T_4 - T_3}{T_6 - T_5} \tag{1}$$

The combustor outlet temperature exhibited by a contemporary industrial gas-turbine typically falls within the range of approximately 1400°C, whereas tower-mounted solar receivers presently encounter limitations with temperatures below 950°C. Consequently, the upper threshold for the maximum nominal solar fraction achievable by a conventional industrial gas-turbine is estimated to hover around 50%.

To mitigate the collective carbon emissions, a pivotal parameter for power plants revolves around the annual fuel-electric conversion efficiency. This metric is contingent not only upon the efficiency of the power block conversion and the nominal degree of solar integration but, more significantly, on the temporal extent of solar operation. For an idealized cycle, the annual fuel-electric efficiency can be approximated using following equation, drawing upon the conversion efficiency (η_{cycle}), the nominal solar share ($f_{sol,nom}$) of the power generation cycle, the total operational hours (hop), and the equivalent number of full-load solar operating hours ($h_{sol,eq}$) [13]. Once the conversion efficiency and nominal solar share of the hybrid solar gas-turbine power plant are established, the annual fuel-electric efficiency is contingent solely upon the fraction of total operating hours during which solar heat is furnished to the system. Augmenting the duration during which the solar collector imparts nominal heat to the system serves as a means to enhance the overall fuel-electric efficiency [11].

$$\eta_{fuel} = \frac{\eta_{cycle}}{1 - f_{sol,ann}} = \frac{\eta_{cycle}}{1 - f_{sol,nom} \times \frac{h_{sol,eq}}{h_{op}}}$$

The dimensions of the solar collector field can be articulated in relation to the solar multiple (SM), as delineated by (2), where it is defined as the quotient of the nominal thermal power dispensed by the field (Q_{field}) to the nominal power requisitioned by the receiver (Q_{rec}) [15]. The nominal yield from the heliostat field is commonly specified, accounting for a direct normal irradiation of 850 W/m2, precisely at solar noon during the Equinox (either on the 21st of March or the 22nd of September).

$$\text{SM}=\frac{Q^{+}_{field,nom}}{Q^{+}_{rec,nom}} \quad (2)$$

The tower piping can be conceptualized as a counter-flow heat exchanger when considering heat transfer. The comprehensive heat transfer, denoted as Q, can be calculated using the equation below, based on the effectiveness-NTU (Number of Transfer Units) methodology. In this equation, ε represents the heat exchanger effectiveness, M_{main} signifies the mass flow rate through the tower, c_p denotes the specific heat capacity of the fluid, and T_2 and T_4 stand for the temperatures at the compressor discharge and receiver outlet, respectively.

$$Q=\varepsilon \times M_{main} \times c_p \times (T_4 - T_2)$$

Pressure losses within the tower piping arise from various phenomena. The total pressure drop, denoted as ΔP_{tot}, is determined by following equation, which sums up the losses occurring during the extraction of the main air-flow after the compressor (ΔP_{ext}), the friction losses within the piping itself (ΔP_{pipe}) during both ascent and descent of the tower, and the losses incurred during the return of the heated air to the gas turbine (ΔP_{ret}) [15].

$$\Delta P_{tot} = \Delta P_{ext} + \sum \Delta P_{pipe} + \Delta P_{ret}$$

4 ANALYSIS OF THE TASHKENT GAS TURBINE CHP

In the Tashkent Combined Heat and Power (CHP) facility, a Hitachi gas turbine has been installed, boasting a power output of 28.1 MW and an electrical efficiency of 34.2%. The flue gases emanating from the turbine are directed towards the Heat Recovery Steam Generator (HRSG) at a temperature of 553°C. The primary objective of the HRSG is to generate steam with specific parameters: 36 bar pressure, 416°C temperature, and a mass flow rate of 46 tons per hour. Subsequently, the produced steam is channeled to the steam turbine for further utilization.

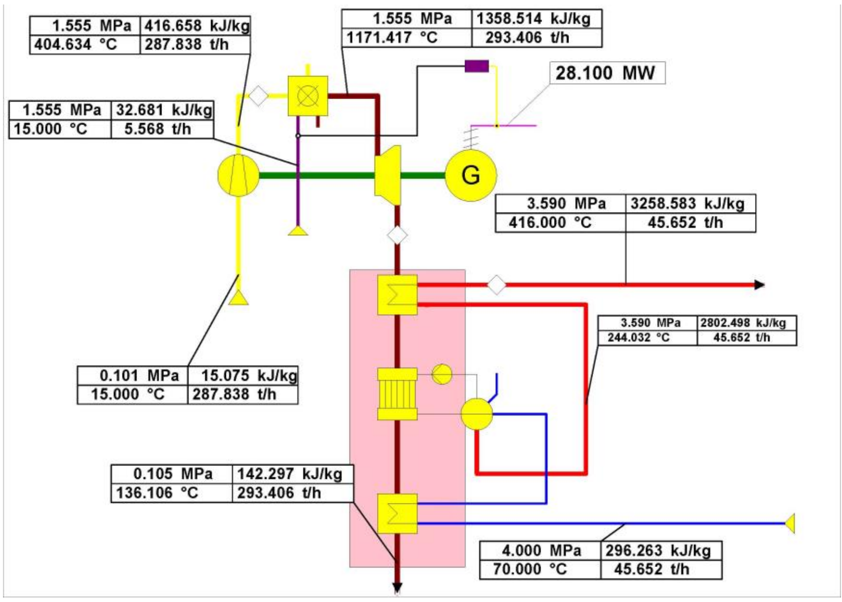


Figure 3: A simulation model of the H27 gas turbine combined heat and power (CHP) system has been created using Ebsilon®Professional software.

The feedwater introduced into the HRSG system initiates at a temperature of 70°C and a pressure of 40 bar. Initially, the feedwater undergoes a heating process within the economizer, elevating its temperature to 240°C, before being directed to the steam generator. The steam generator is responsible for generating saturated steam at a temperature of 244°C [15].

This comprehensive system ensures the efficient conversion of gas turbine exhaust heat into steam, subsequently harnessing the thermal energy to drive a steam turbine, exemplifying a cogeneration approach for enhanced energy utilization in the Tashkent CHP facility.

To investigate the correlation between CO_2 emissions and the solar share, a computational model of the extant H27 gas turbine combined heat and power (CHP) system was constructed using Ebsilon®Professional software. The simulation model, conducted at an ambient temperature of +15°C, is presented in Figure 3.

Additionally, the Carnot factor-energy diagram of the Heat Recovery Steam Generator (HRSG) at the same ambient temperature is illustrated in Figure 4.

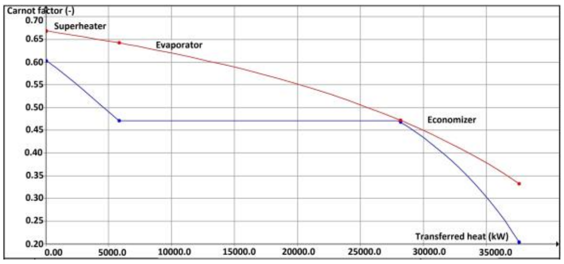


Figure 4: Carnot factor-Energy diagram of HRSG.

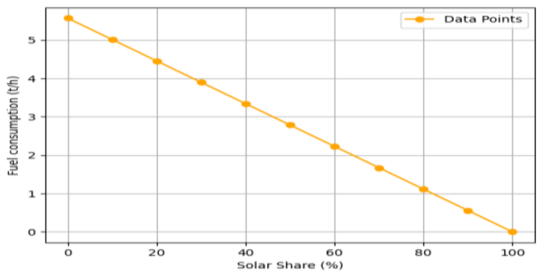


Figure 5: Fuel consumption-Solar share of 28.1 MW SHGT.

Ebsilon software was employed for the comprehensive analysis of emissions emanating from an extant H27 gas turbine in correlation with its power output. The simulation model, presented in Figure 3, is representative of a scenario wherein the atmospheric temperature attains a specific value, specifically +15°C. Furthermore, Figure 4 elucidates the Carnot-factor-Energy diagram, offering insights into the thermodynamic efficiency of the system under consideration.

Figure 5 illustrates the changes in fuel consumption resulting from the integration of a solar tower device into a 28.1 MW gas turbine. Concurrently, as fuel consumption decreases, the emissions of harmful gases also decline proportionally

5 CONCLUSIONS

The integration of a solar tower into the 28.1 MW gas turbine, as simulated in the Ebsilon program, has yielded noteworthy outcomes with implications for both environmental sustainability and operational efficiency. The analysis of the hybrid system reveals a discernible reduction in fuel consumption, a critical metric indicative of improved resource utilization and decreased reliance on traditional fossil fuels. This decrease in fuel consumption, as depicted in Figure 5, correlates directly with a proportional reduction in the emission of harmful gases, showcasing the potential environmental benefits of incorporating renewable energy sources

Furthermore, the simulation results underscore the adaptability and efficacy of the hybrid system in response to varying solar shares. The correlation between the solar share and fuel consumption suggests that the system can be dynamically optimized to harness solar energy efficiently, thereby enhancing overall performance and minimizing the environmental footprint [16]. The Ebsilon simulation offers valuable insights into the intricacies of the integrated system, enabling a comprehensive understanding of its behavior under diverse operating conditions.

In conclusion, the integration of a solar tower into the 28.1 MW gas turbine, as elucidated by the simulation results, holds promise for advancing sustainable energy practices. The observed reductions in fuel consumption and emissions underscore the potential of such hybrid configurations in contributing to cleaner and more efficient power generation systems. These findings contribute to the growing body of knowledge aimed at fostering environmentally conscious and technologically innovative solutions within the realm of power generation.

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