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Advancing Sustainable Energy through Integrated Solar-Biogas Systems: A Renewable Substitute for Fossil Fuels

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ABSTRACT

This study investigates the feasibility of integrating biogas derived from municipal solid waste with solar energy in a hybrid power plant located near a municipal landfill site. The hybrid system comprises photovoltaic panels and a gas turbine that currently operates on natural gas. The primary objective of this research is to replace natural gas with biogas in order to enhance energy security, reduce greenhouse gas emissions, and improve sustainable waste management. Detailed data on the volume and characteristics of municipal waste were collected, and the biogas production potential from the landfill site was calculated. Simulations were conducted using PVsyst and HOMER software. Integrating biogas as a sustainable and reliable energy source compensates for the intermittency of solar energy and ensures a more consistent electricity generation throughout the year. This system not only reduces dependence on fossil fuels but also contributes to the sustainable management and control of municipal waste. The results of this research demonstrate the high potential of this hybrid system in reducing operational costs, improving energy efficiency, and mitigating environmental impacts. Furthermore, this project serves as an educational platform for students and researchers, offering opportunities to study renewable energy technologies. The study presents innovative solutions for the optimal utilization of local resources and proposes a model for similar projects in other regions, which could lead to a more sustainable and efficient energy future.

Keywords: Hybrid power plant, biogas, solar energy, renewable energy.

1 Introduction

The global energy sector is currently experiencing a profound shift, with renewable energy sources taking on a vital role in tackling the dual issues of climate change and energy security [1]–[4]. Resources like solar and wind energy offer long-term solutions to reduce greenhouse gas emissions and lessen dependence on limited fossil fuel supplies [5]–[9]. Nonetheless, the inherent intermittency of some renewables—especially solar energy—creates challenges in ensuring a stable and continuous energy supply. One viable solution to manage this variability involves storing excess energy in the form of hydrogen. Surplus electricity generated from solar panels can be directed toward water electrolysis to produce hydrogen, which can then be stored and later used to generate electricity or serve other energy demands. While this method enhances the stability of renewable integration, it comes with high costs. Another effective alternative is the deployment of hybrid energy systems within microgrids. These systems leverage a combination of diverse energy sources to deliver more reliable and resilient power. By merging complementary energy types, hybrid systems improve both the robustness and efficiency of energy networks.

Biogas stands out as an optimal companion for solar energy in such hybrid setups. Due to its dispatchable and steady output characteristics, biogas can counterbalance the fluctuations associated with solar energy production. This compatibility makes biogas a valuable asset in hybrid configurations, offering both environmental advantages and dependable performance in microgrid applications.

Research focusing on solar and biogas energy underscores their combined potential in addressing ecological and economic issues. Multiple studies point to their benefits in electricity generation, reducing emissions, and boosting energy efficiency. Investigations involving wastewater treatment plants (WWTPs) show that integrating biogas with solar photovoltaic systems can cut greenhouse gas emissions significantly and supply up to 88% of yearly energy needs through renewable sources [10]. In Brazil, biogas has been recognized as a more cost-effective solution compared to solar PV for rural communities, prompting recommendations for supportive public policies to promote its adoption [11]. Technical and economic assessments of hybrid renewable energy systems (HRES) that incorporate both solar PV and biogas have reported promising results, such as effective energy recovery from cassava wastewater and high internal rates of return [12]. Studies of engine-generators powered by agricultural waste-derived biogas have demonstrated increased efficiency and reduced specific fuel consumption at higher loads, indicating feasibility for both grid-tied and standalone operations [13]. Furthermore, adding hydrogen to biogas in spark-ignition engines has been found to enhance combustion efficiency and lower CO₂ emissions, presenting a cleaner power generation alternative [14].

Efforts to improve the accuracy of biogas emission predictions from landfills through localized data and refined models have highlighted the potential of biogas in mitigating environmental impacts via energy generation [15]. Innovative techniques for converting gasoline engines to biogas-fueled systems have also shown economic and ecological benefits, especially when combined with LPG as a supplementary fuel [16]. Comparative studies evaluating biogas against gasoline and LPG in generators suggest biogas performs better in terms of brake-specific fuel consumption and thermal efficiency, although combustion processes may require further refinement [17]. Additional research on biogas production from unmanaged waste in Brazil has suggested new ways to optimize landfill methane use for power generation and reduced CO₂ emissions [18]. Emerging technologies such as microbial electrolysis cells and nanobubble technology are also boosting methane yields, enhancing biogas competitiveness in the renewable energy landscape [19]. Meanwhile, techno-economic evaluations of mini biogas electricity plants (MBEPs) in Zimbabwe emphasize their potential to alleviate energy poverty in off-grid regions while encouraging sustainable agricultural practices [20].

This study explores the feasibility of replacing natural gas with biogas derived from a municipal landfill in Kermanshah, within a solar-biogas hybrid energy system. The main objective is to evaluate both the environmental and financial benefits of utilizing biogas as a fuel in a multi-fuel generator setup. Throughout the study, extensive data were collected regarding municipal waste output in Kermanshah, and the potential for biogas generation was thoroughly estimated. Results show that biogas can significantly decrease greenhouse gas emissions and fuel costs, while also advancing sustainable waste management efforts. Moreover, this approach contributes to the broader adoption of renewables by increasing their share in the total energy portfolio. This research also addresses the challenge of renewable energy intermittency, emphasizing the importance of optimized resource management—an area that has garnered considerable attention in recent literature [21], [22]. Another proposed solution involves energy storage systems designed to manage this uncertainty [23]. The paper offers actionable strategies and forward-thinking recommendations to maximize the utilization of local renewable energy resources, ultimately supporting the transition to a more sustainable and energy-efficient future.

The structure of the paper is as follows: Section 2 presents the system under study and the research methodology. Section 3 details the results of the simulations and calculations. Finally, the paper concludes with a summary of the key findings in the last section.

2 Studied System

Biogas is highly significant as a renewable energy source because it not only helps reduce dependence on fossil fuels but

also plays an effective role in waste management and mitigating environmental impacts [24].



Fig. 1. Aerial view of the municipal waste management site and Kermanshah university of technology power plant [8].

Biogas is produced from decomposition of organic materials such as municipal waste, and its production process reduces waste volume.

2.1 Utilization of Biogas Derived from Urban Waste

biogas serves as a local energy source that can contribute to energy supply. Utilizing biogas in these areas not only leads to electricity and heat generation but also produces by-products that can be used as high-quality organic fertilizer for agricultural lands. Although the fuel for the gas turbine generator is planned to be supplied by natural gas, the idea of utilizing this renewable energy source could be a subject of study in this project.

The hybrid power plant at Kermanshah University of Technology is located 1.6 kilometers away from the municipal waste site. Establishing agreements and planning to harness this potential could reduce the gas consumption of the turbine generator and take a significant step toward urban waste management. For this purpose, precise data on the municipal waste site, including daily waste input volume, its characteristics, and storage conditions, was required and is presented in TABLE I. Fig. 1 shows an aerial view of the waste site along with the location of the university power plant.

The description of this section initially pertains to the solar power plant. The photovoltaic panels of this plant have been installed. The location of these panels is in the car park canopy section of the university. This location is one of the suitable spaces without shading. The data in this table has been obtained from official and reliable urban sources. For verification, it has been compared with other previously published reputable sources and has been confirmed [25]-[27].

2.2 Hybrid power plant of university

The use of hybrid renewable energy systems in the form of microgrids is a suitable solution to solve their uncertainty [28]-[29]. of course, this requires a suitable controller to control voltage and power [30]-[31]. It is better to simulate and analyze them in a suitable software before implementing such

systems [32]-[33]. The presence of a hybrid photovoltaic-biogas system in universities is highly significant, as it not only provides sustainable energy and reduces electricity costs but also serves as an educational and research platform for students and faculty members. These systems allow students to gain hands-on experience with renewable energy technologies and conduct research on optimizing energy production and storage.

TABLE I. Specifications of Monthly Waste Input to the Urban Management Center

	Month	Daily Average (Ton)	Total Waste (Ton)
1	January	103.4	3105
2	February	108	3241
3	March	121	3757
4	April	118	3660
5	May	113.5	3519
6	June	112.8	3497
7	July	110.9	3438
8	August	109	3379
9	September	113.8	3528
10	October	105.6	3171
11	November	106.1	3182
12	December	110.1	3307

Utilizing such technologies helps reduce greenhouse gas emissions, promote a culture of clean energy use, and move the university. Furthermore, it ensures a reliable power supply for the university, especially in the face of electricity imbalances in Iran. The output current characteristic of a PV is described by (1) [34]-[36].

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(u + IR_s)}{AKT}\right) - 1 \right] - \frac{(u + IR_s)}{R_{sh}} \quad (1)$$

The current I_{ph} represents the generated current of the PV system, influenced by solar radiation and temperature. As radiation intensity increases, I_{ph} also increases. The output characteristics of a PV cell are defined as follows. Here, I_0 is the reverse saturation current, primarily dependent on temperature (measured in amperes). q is the charge of an electron, T is temperature, K is Boltzmann's constant, and A is the ideality factor (1.2 for monocrystalline silicon). I and U denote the output current and voltage of the PV, respectively. R_s and R_{sh} are the series and shunt resistances. In an ideal PV cell, R_{sh} is considered infinite, preventing any additional current paths. Similarly, R_s is assumed to be zero, eliminating voltage drop before the load. Since R is very small, I_{ph} is approximated as I_{sc} . Under open-circuit conditions, $U = U_{oc}$, while at the maximum power point (MPP), $U = U_m$ and $I = I_m$ hold. Thus, the characteristic equation of the PV cell's output current is given by (2).

$$I = I_{sc} \left\{ 1 - C_1 \left[\exp\left(\frac{u}{C_2 U_{oc}}\right) - 1 \right] \right\} \quad (2)$$

The values of C_1 and C_2 are defined in (3).

$$C_1 = \left(1 - \frac{I_m}{I_{sc}} \right) \exp\left(-\frac{U_m}{C_2 U_{oc}} \right) \quad (3)$$

$$C_2 = \left(1 - \frac{I_m}{I_{oc}} \right) / \ln\left(1 - \frac{I_m}{I_{sc}} \right)$$

In (3), U_m represents the voltage at MPP, and U_{oc} is the open-circuit voltage. Since the PV array's output power depends on these parameters, the relationship is expressed in (4).

$$P(u) = UIsc \left\{ 1 - C_1 \left[\exp\left(\frac{u}{C_2 U_{oc}}\right) - 1 \right] \right\} \quad (4)$$

PV cell efficiency is affected not only by internal resistances but also by environmental factors such as solar radiation, module temperature, dust accumulation, and shading from clouds, trees, or buildings.



Fig. 2. Solar Photovoltaic Part of university hybrid Power Plant [8].

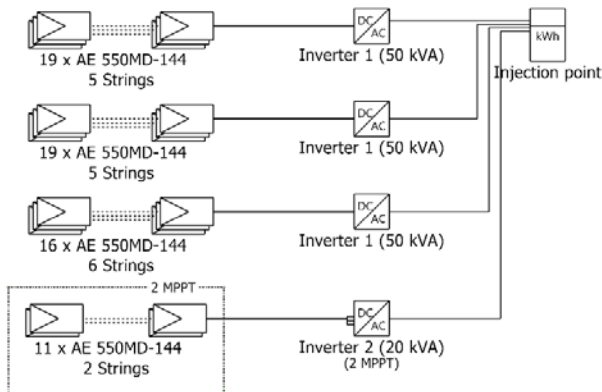


Fig. 3. Single-line diagram of photovoltaic part.

The standard PV parameters $I_{sc_{ref}}$, $U_{oc_{ref}}$, $U_{m_{ref}}$, and $I_{m_{ref}}$ are defined under reference conditions ($S_{ref} = 1000 \text{ W/m}^2$, $T_{ref} = 25^\circ\text{C}$), allowing the calculation of I_{sc} , U_{oc} , U_m , and I_m using (5).

$$\begin{aligned} I_{sc} &= I_{sc_{ref}} \times \frac{S}{S_{ref}} (1 + a \times \Delta t) \\ U_{oc} &= U_{oc_{ref}} \cdot \ln(e + b \times \Delta t) (1 - c \times \Delta t) \\ I_m &= I_{m_{ref}} \cdot (1 + a \times \Delta t) \\ U_m &= U_{m_{ref}} \cdot \ln(e + b \times \Delta t) (1 - c \times \Delta t) \end{aligned} \quad (5)$$

The output power of the PV cell is determined by the product of voltage and current when a load is connected.

$$\begin{aligned} P_{out} &= V_{out} \times I_{out} \\ P_{max} &= V_{max} \times I_{max} \\ P_{max} &= V_{oc} \times I_{sc} \times FF \\ \eta_{ec} &= \frac{P_{max}}{P_{in} \frac{V_{oc} \times I_{sc} \times FF}{I(t) \times A_c}} \end{aligned} \quad (6)$$

The process of connection and commissioning of this section has been completed. The panels are connected to the inverter and equipped with maximum power tracking, voltage, and AC power frequency control, enabling the generated energy to be used or injected into the grid (Fig. 2). Fig. 3 shows a part of the power plant structure (one-third of power plant).

The thermal efficiency of the gas turbine represents the ratio of the net power output (W_{net}) to the chemical energy contained in the incoming biogas ($\dot{m}LHV$). Equations (7), (8), and (9) describe the performance of the biogas system [37].

$$\eta_{th} = \frac{W_{net}}{\dot{m}LHV} \quad (7)$$

η_{th} is Thermal efficiency of the turbine, W_{net} is Net power output of the turbine (W). \dot{m} is Mass flow rate of biogas (kg/s) and LHV is Lower heating value of biogas (J/kg).

$$r_p = \frac{P_{out}}{P_{in}} \quad (8)$$

Equation (8) represents the pressure ratio in the compressor, which significantly affects the overall performance of the system. A higher-pressure ratio generally leads to increased efficiency but also requires more compression work. r_p is Compressor pressure ratio. P_{out} is compressor outlet pressure (Pa) and P_{in} is compressor inlet pressure (Pa).

The power generated by the turbine is calculated based on the temperature difference between its inlet and outlet. The greater the difference, the higher the power output (9).

$$W_{turbine} = \dot{m} C_p (T_{inlet} - T_{outlet}) \quad (9)$$

$W_{turbine}$ is Turbine power output (W). C_p is Specific heat capacity at constant pressure (J/kg.K). Turbine inlet temperature (K) and turbine outlet temperature (K) are there in (9). The general structure of the biogas generator turbine and its various components, which include the biogas combustion process and energy production through the turbine's rotation followed by the generator, is shown in Fig. 4 and Fig. 5. A 1 MW natural gas turbine will be located at the hybrid power plant. These units have an output voltage of 3.3 kV.

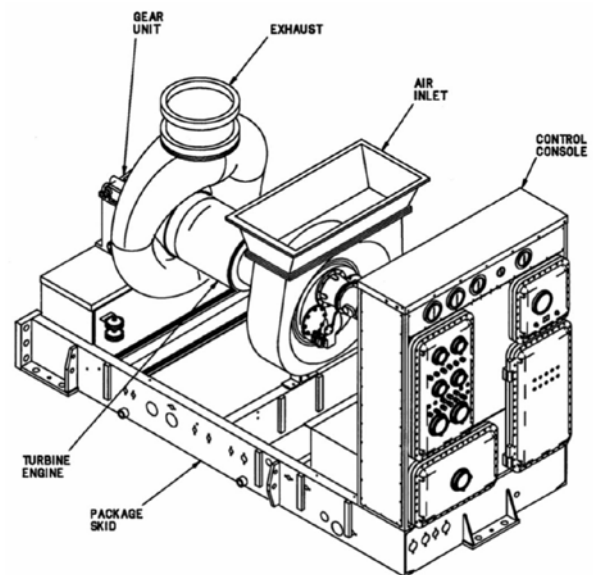


Fig. 4. Overall structure and introduction of the mechanical components of the biogas turbine generator [8].

The turbine generator (Fig. 5) primarily plays a backup role during power outages. This natural gas unit, alongside the university's solar power plant, forms a hybrid power plant. A major challenge in increasing the operating time of this turbine generator unit exists. Iran is facing an energy imbalance issue. During the cold season, the use of natural gas for this unit is subject to significant restrictions. For this reason, this research paper has been conducted to explore the possibility of using clean energy as an alternative to fossil fuel natural gas and to increase electricity production.



Fig. 5. Turbine generator part of the hybrid power plant is set to be installed [8].

3 Results

This section presents the performance results of a hybrid solar-biogas power plant. The PVsyst software was utilized to analyze the electricity production from the photovoltaic solar system, while the HOMER was employed to evaluate the gas turbine generator system. The primary objective of this section is to assess the feasibility of replacing natural gas with biogas, a renewable energy source, as a sustainable alternative in the energy generation process. The results of the solar sector were determined with the PVsyst and the results of hybrid power plant, which includes biogas, were determined with the Homer.

3.1 Solar Energy

In the photovoltaic solar energy section of this research, the performance of a grid-connected photovoltaic system in Kermanshah, Iran, is analyzed (Fig. 6). The system utilizes fixed-tilt solar panels with no shading, and real meteorological data is employed to predict its performance. The technical specifications include the use of several different subsets of modules and inverters, along with calculations of the system's nominal power and energy output. The results indicate that the system operates with adequate efficiency and has been able to generate a significant amount of electricity throughout the year. The energy loss analysis shows that factors such as module temperature, equipment quality, and wiring have been examined, and the losses have been precisely measured. Additionally, the reduction in carbon dioxide emissions is highlighted as a key environmental achievement of the project, with estimates suggesting that this system makes a significant contribution to reducing greenhouse gases. Overall, the

simulation results in PVsyst, a state-of-the-art software for analyzing the performance of solar systems, evaluate the system's performance positively in terms of energy production and environmental impacts. The photovoltaic system of this power plant is of the grid-connected.

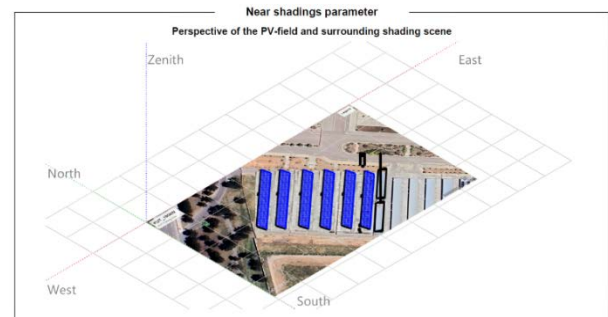


Fig. 6. Perspective of the PV-field and surrounding shading scene.

The system is installed on a fixed structure with a tilt angle of 20 degrees and an azimuth orientation of -42.5 degrees. These settings are optimized to maximize solar energy absorption and ensure high efficiency. The total number of solar panels used in this power plant is 990, which supply the generated energy to 12 inverter units. The solar panels used in this power plant are manufactured by AE Solar and are of the AE 550MD-144 model. Each panel has a nominal power of 550 watts peak (Wp). The total surface area of the panels contributes to efficient energy generation.

The project features a grid-connected photovoltaic system, designed to generate electricity through solar panels and deliver it directly to the city's electrical grid for consumer use. Located in Kermanshah, Iran, the system operates at an altitude of 1,705 meters above sea level, with an approximate latitude of 34 degrees North and longitude of 47 degrees East. Meteorological data for the project is sourced from Meteororm 8.0. The albedo value, which quantifies the proportion of sunlight reflected by the ground surface, is 0.20, indicating that 20% of incident sunlight is reflected by the terrain (e.g., soil or grass), while the remaining 80% is absorbed.

The photovoltaic system has a peak power capacity of 678 kilowatt-peak (kWp), representing the maximum power output achievable under ideal conditions. It comprises 1,176 solar panels, with inverters that convert the direct current (DC) generated by the panels into alternating current (AC) suitable for grid integration, providing a total inverter capacity of 658 kilowatts AC. The system's power ratio of 1.030 indicates that the PV array's capacity slightly exceeds that of the inverters, a standard design approach to optimize performance. The system achieves a specific production of 2,169 kilowatt-hours per kilowatt-peak per year, meaning each kilowatt of installed capacity generates 2,169 kWh annually. With a performance ratio of 91.56%, the system converts 91.56% of the received solar energy into usable electricity, reflecting a highly efficient design. The absence of shading effects, such as from buildings or trees, ensures maximum solar irradiation on the panels.

System losses, which reduce electricity production, are minimal. Module quality loss is negligible at 0.0%, indicating high-quality panels with no significant performance degradation. Similarly, module mismatch losses are 0.0%, confirming that all panels operate in perfect synchronization, with no energy loss due to performance inconsistencies. Thermal losses are reported as zero, with a thermal coefficient of 0.0 W/m²K, which is unusual and may require further verification. Losses due to the angle of incidence occur when sunlight strikes the panels at an angle, causing some energy to be lost through reflection. The panels are equipped with an anti-reflective coating, enabling effective energy capture across various angles: 100% at 0 degrees (perpendicular), 99.9% at 30 degrees, 98.7% at 50 degrees, 96.2% at 60 degrees, 89.2% at 70 degrees, 81.6% at 75 degrees, 68.1% at 80 degrees, 44% at 85 degrees, and 0% at 90 degrees (horizontal). DC wiring losses, resulting from a global wiring resistance of 10 milliohms, account for a 1.5% energy loss under standard test conditions due to resistance in the cables connecting the panels to the inverters.

Fig. 7, including a loss diagram that visually illustrates energy losses at various stages, such as reflection, wiring (1.5%), and inverter conversion, with no losses attributed to module quality or mismatch.

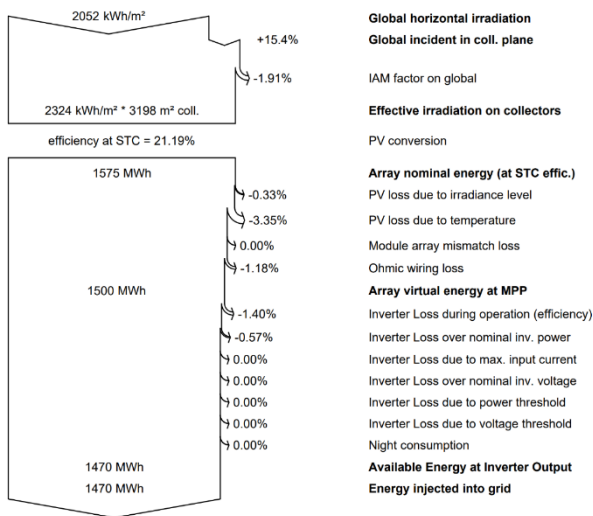


Fig. 7. Loss diagram

Predefined graphs likely depict monthly electricity production, temperature variations, or system performance under different conditions, with higher production expected in summer due to increased solar irradiation. The CO₂ emission balance analysis highlights the environmental benefits of the system. With an annual production of approximately 1,470,582 kWh, calculated from the specific production of 2,169 kWh/kWp/year and a capacity of 678 kWp, the system significantly reduces CO₂ emissions by replacing fossil fuel-based electricity with solar energy.

In summary, the system, with its capacity, is designed to produce approximately 1.47 million kWh of electricity annually. Operating at a performance ratio of 91.56%, it

minimizes energy losses, with only 1.5% attributed to wiring and variable losses due to the angle of incidence. The absence of shading and the use of anti-reflective coatings enhance energy capture, making the system a highly efficient and environmentally sustainable solution for electricity production in Kermanshah.

In the energy conversion section, the system includes a combination of different inverter models. These include 9 units of the Blueplanet 50.0 TL3-INT XL model along with 3 additional units. The inverters are responsible for converting the energy generated by the solar panels into alternating current (AC) electricity usable in the grid.

3.2 Biogas Energy

Based on the simulation of the power generation system in HOMER software, a hybrid power plant composed of two renewable energy sources, biogas and solar energy, has been modeled, with the results of the biogas section utilized in this study. A biogas generator has been designed to meet the energy demand. The system is configured in a way that renewable energy plays a significant role in power generation, and an auxiliary generator is employed to optimize efficiency and fulfill the load requirements. Total electrical load served duration curve is shown in Fig. 8. The monthly production chart indicates that the system generates electricity uniformly throughout the year (Fig. 9).

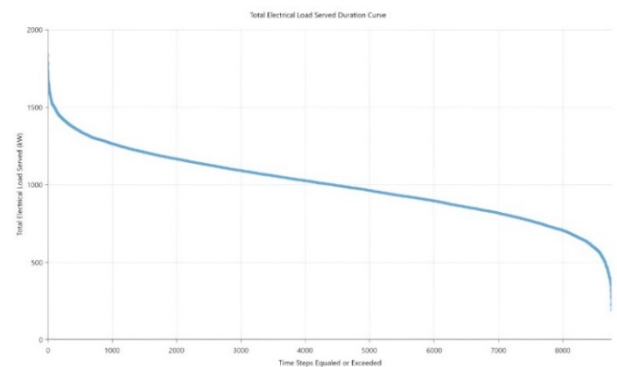


Fig. 8. Total electrical load served duration curve (Biogas energy)

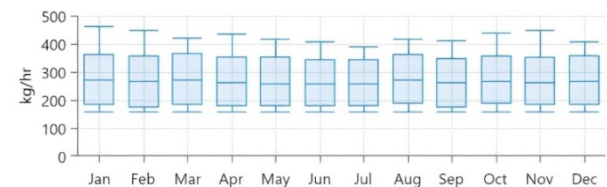


Fig. 9. Average amount of solid waste in the months.

The nominal capacity of hybrid power plants is shown in Fig. 9. In addition, the amount of load consumed by the university has an average value of 300 kW. This design has been proposed to reduce dependence on fossil fuels and lower the system's operational costs. In this analysis, the balance between power generation and optimal consumption has been

examined, and the penetration level of renewable energy has been fully assessed. Furthermore, the amount of surplus electricity produced and the system's ability to minimize environmental impacts are among the key highlights of this simulation.

This simulation demonstrates in HOMER, that the designed hybrid system is capable of fully meeting energy demands using renewable resources, without causing any shortfall in load supply. The high solar energy production, combined with the support of the biogas generator, ensures system stability. However, the presence of a significant amount of excess energy indicates potential for system design improvements, such as adding an energy storage system (battery) or utilizing the surplus energy for other applications. From an economic perspective, the high NPC (Net Present Cost) and COE (Cost of Energy) may pose challenges for implementation, but the 100% renewable fraction and the reduction in environmental impacts make this system an attractive option for sustainable energy development.

3.3 Hybrid Power Plant

The combination of solar energy and biogas has proven to be an excellent solution for energy production. This hybrid system has generated significantly more energy than the university's total consumption requirements. Moreover, the uncertainty associated with solar energy, such as its intermittent availability, has been effectively eliminated thanks to the continuous and reliable presence of biogas as a complementary energy source. The simulation results of the solar and biogas parts are shown in Fig. 10. According to these results, the use of biogas energy increases the production power of the power plant to a great extent and helps the system to deal with the uncertainty of solar energy.

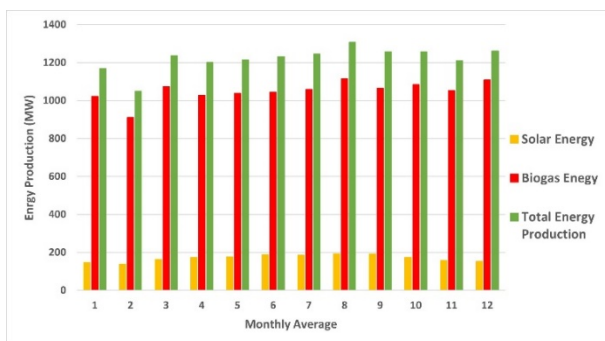


Fig. 10. Power produced in hybrid renewable power plant per month.

4 Conclusion

The integration of biogas and solar energy in a hybrid power plant offers significant potential for sustainable energy generation, especially in regions like Kermanshah, Iran. By harnessing biogas produced from municipal waste, this system not only reduces dependence on fossil fuels but also contributes to effective waste management. The combination

of biogas and photovoltaic (PV) systems ensures a steady and reliable power supply for Kermanshah University of Technology, thereby reducing operational costs and mitigating the environmental impacts of traditional energy sources. The implementation of the hybrid power plant demonstrates the feasibility of utilizing biogas as an alternative to natural gas, addressing the energy imbalance challenges faced by Iran.

This hybrid approach not only meets the electricity demand but also promotes environmental sustainability through reduced greenhouse gas emissions. Additionally, the educational benefits for students and researchers, along with the promotion of renewable energy technologies, highlight the broader societal impact of such systems. With the successful integration of the PV system and biogas generator, the power plant at Kermanshah university of technology stands as a model for future renewable energy projects. By optimizing energy production, minimizing waste, and promoting clean energy practices, this hybrid power plant represents a crucial step towards a sustainable and energy-efficient future. The results of this study offer valuable insights for similar initiatives globally, with the potential to replicate and expand upon the benefits demonstrated in Kermanshah.

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Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

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