applied sciences

Article

Evaluating a Solar–Biogas Hybrid Renewable Power Plant by Heating the Anaerobic Digester Using the Rejected Heat of Rankine Cycle in Idlib, Syria

Ayman Abdul Karim Alhijazi [1], Ahmad Firas Alloush [1] and Radwan A. Almasri [2,*]

[1] Department of Mechanical Power Engineering, Collage of Mechanical Engineering, Idlib University, Idlib 5100, Syria; ayman.abdulkarim.alhijazi@idlib-university.com (A.A.K.A.); ahmad.firas.alloush@idlib-university.com (A.F.A.)

[2] Department of Mechanical Engineering, College of Engineering, Qassim University, Buriadah 51452, Saudi Arabia

* Correspondence: ra.almasri@qu.edu.sa

Abstract: This research includes modeling and studying the performance improvement of a hybrid renewable energy power plant using the modeling software Greenius in Idlib, Syria. The system consists of solar parabolic trough collectors and an anaerobic digester for generating biogas. This study included a practical experiment for generating biogas using five identical digesters operating at five different temperatures. The raw material was a mixture of 81% food waste and 19% human waste, and average temperatures were as follows: 49.6, 45.9, 43.5, 37.5, and 33.2 °C. Modeling operations were conducted for each case, as well as for the case corresponding to the highest growth rate of methanogenic bacteria theoretically. The modeling processes were conducted at 11 different values for the storage capacity from Full Load Hours (FLHs) 0 to 10 and by varying the solar multiple factor (SM) from 1 to 8. This study showed that when operating as a net solar plant, the lowest value for the cost of produced electricity (LCOE) was 0.1785 EUR/kWh at FLHs = 5 h and SM = 2, while the annual electricity production was 25.21 GWh. The maximum annual electricity production was 48.66 GWh, achieved at FLHs = 10 h, SM = 8, and the LCOE = 0.2896 EUR/kWh. It is possible to obtain annual electrical energy of 39.7 GWh, which was about 82% of the maximum possible annual production, at a cost of LCOE = 0.1864 EUR/kWh, which is less than 5% higher than the lowest possible cost. When operating as a hybrid plant with an annual capacity factor of 1 (full load), it is discovered that the lowest value of energy produced is in the third scenario at t_{AD} = 43.52 °C and t_c = 63.5 °C, with FLHs = 0 h and SM = 1, with the LCOE = 0.1283 EUR/kWh.

Keywords: anaerobic digester; biogas; biomass; power plant; renewable energy; solar energy

check for updates

Citation: Alhijazi, A.A.K.; Alloush, A.F.; Almasri, R.A. Evaluating a Solar–Biogas Hybrid Renewable Power Plant by Heating the Anaerobic Digester Using the Rejected Heat of Rankine Cycle in Idlib, Syria. *Appl. Sci.* **2024**, *14*, 12027. https://doi.org/10.3390/app142412027

Academic Editors: Arsalan Najafi, Zbigniew Leonowicz, Michał Jasiński, Omid Homaee and Luca Fiori

Received: 7 October 2024
Revised: 3 November 2024
Accepted: 2 December 2024
Published: 23 December 2024

1. Introduction

Integrating renewable energy sources is essential to address global energy demands while minimizing environmental impacts. The need for innovative and sustainable energy solutions is even more critical in regions like Idlib, Syria, where energy infrastructure has been severely disrupted. This study explores the potential of a solar–biogas hybrid renewable power plant, which combines the benefits of solar energy and biogas production to create a more reliable and sustainable energy supply. In this hybrid system, a unique approach is proposed: using the condenser of a steam turbine cycle to heat the anaerobic digester (AD), which is a key component in biogas production. The excess heat from the steam turbine is redirected to maintain optimal temperatures in the digester, improving the efficiency of biogas generation. This integration not only enhances energy production but also maximizes the use of available resources, making it a highly efficient and eco-friendly solution. By focusing on Idlib, Syria, this study highlights the potential for renewable energy systems to support regions with limited access to conventional power sources, contributing to energy resilience and environmental sustainability. The hybrid solar–biogas model represents a step forward in addressing both energy needs and the challenges of climate change, offering a blueprint for similar regions worldwide.

This study examined the technical and economic feasibility of a hybrid solar–biogas power plant in Idlib, Syria; Greenius 4.9.0.1 software was used for the simulation, and the supposed system includes an AD for producing biogas and solar parabolic trough collectors. A traditional steam turbine power block uses heat to produce electricity. Five identical digesters running at five different temperatures were used in a practical biogas generation experiment as part of this study. Using this hybrid system in the Idlib region may provide in several benefits, including the following:

- Ensuring the stability of the electricity produced;
- Disposing of waste in a clean and energy-producing way;
- Producing bio-fertilizers;
- Creating new job opportunities for the local community.

Hybrid plants can generate electricity from renewable energy, utilizing two or more renewable energy sources. Hybrid power plants are classified according to the way energy sources are connected into two systems [1]:

a. Hybrid power plants with electrical connection: where there is no direct relationship between energy sources, and none affects the other, and each energy source has its own independent generator; the plant requires a synchronization system between the two electrical currents to operate simultaneously, such as a wind turbine or photovoltaic (PV) system;
b. Hybrid power plant with energy source connection: there is a relationship between energy sources before reaching the generation units. Table 1 illustrates the advantages and disadvantages of both types of conjunction.

Table 1. Advantages and disadvantages of both types of conjunction [2].

	Energy Source Conjunction	**Electrical Conjunction**
Unit of generation	One for all sources of energy	One for each source of energy
Need for a synchronization system	No	Yes
Connection between the sources	Yes	No
Ideal for	Biomass, solar thermal, geothermal, fossil fuel systems	Wind turbines, PV systems, nuclear energy, fuel cells, hydraulic systems, etc.
Efficiency dependence	It depends on the connections between the energy sources	The efficiency of each unit depends on its specifications and is separated from the other

One of the most famous hybrid systems that follows this configuration is the hybrid power plant that combines solar thermal energy and biogas (generated from an AD). Improving the performance of these systems represents a significant benefit for enhancing the utilization of the plant and reducing the cost of the electricity produced.

Syria falls within the economically acceptable range for establishing concentrated solar power (CSP) plants [3], and the city of Idlib can provide wastewater (WW) and municipal food waste to operate a biogas plant, where the population is approximately one million, the average daily solid waste is 260 tons, of which 47.4% is biodegradable organic material, and the average daily sewage is 40,000 m^3 [4]. The amount of biogas from sewage daily per person is 0.018–0.026 m^3/person, which is an average of 0.022 m^3/person according to the International Energy Agency [5].

2. Literature Review

Several studies have used solar thermal or biomass for power generation, but there are limited studies on using solar and biomass in hybrid systems. Mohd et al. [6] looked at the hybrid solar biomass plant's technical, financial, and environmental elements and the necessary resources for deployment and operation. The authors found that hybrid power plants increase the rate of electricity output while mitigating the drawbacks of single-resource plants. They also discussed the possibilities of similar systems in India and other nations. For the CSP plants to be profitable, they are usually constructed in regions that fall between 15- and 40-degree latitude in the subtropical zone in both the northern and southern hemispheres. These regions include the following: Australia, the Southwest of the United States, the Middle East, North Africa, Western China, and Northern Mexico [7]. Thiam et al. [8] presented the results of Sahel's selection of possible regions for hybrid CSP–biomass in a case study of Senegal. The direct normal irradiation (DNI) of the discovered locations is greater than 1600 kWh/m^2 annually. The authors pointed out that the special reduction in CSP–biomass hybrid plants permits locations between 1400 kWh/m^2 per year and 2000 kWh/m^2 per year. According to Peterseim et al. [9], a standalone CSP plant requires DNI values of more than 20 MJ/m^2 per day (about 2000 kWh/m^2 year), with a high biomass potential. As suggested for hybrid solar–biomass systems, Ling et al. [10] investigated the integration of a solar power tower with a solid particle fluidized system in a beam-down arrangement. While studying such a system, problems with reactor scaling, continuous supply/syngas production, and operating temperature were encountered. The goal is to develop a high-temperature hybrid solar–biomass system that can reduce greenhouse gas emissions and direct biomass combustion while increasing the efficiency of converting sunlight into fuel.

The Levelized Cost of Energy (LCOE) is an essential indicator for determining the economic sustainability of renewable energy projects, such as hybrid solar thermal power plants. LCOE is the per-unit cost of building and operating a producing plant during its lifespan, considering startup capital, operational costs, and predicted energy production. Recent research emphasizes the viability of hybrid solar thermal systems that include biomass or other renewable energy sources. The following examples clarify some of these studies and research from around the world. According to Coelho et al.'s study [11] of the Portuguese Algarve region's renewable resource potential for CSP facilities, the region could generate 1244 GWh from biomass sources, 30 GWh from wood processing and agricultural byproducts, and 219 GWh from biogas produced by sewage treatment plants. The study discovered that a 4 MW_{el} hybrid CSP—biogas power plant could have the lowest LCOE of 0.15 EUR/kWh. This system, which combined atmospheric volumetric central receiver system technology with anaerobic digestion of wastewater treatment plant sludge, had a 13-year payback period and an internal rate of return of 11%. Bai et al. [12] reported that solar towers are the optimal CSP technology for hybrid systems' combined heat and power (CHP) generation. According to the study, combining CSP with biomass can generate 50 MW of energy. The hybrid system had a higher annual net solar-to-electric efficiency of 18.13% compared to 15.79% for standalone CSP. It also had a lower LCOE of 0.077 USD/kWh compared to 0.192 USD/kWh. Additionally, the annual biomass consumption is reduced by 22.53% compared to a single-biomass power system with the same capacity. Servert et al. [13] presented research on a 10 MW hybrid power plant with an annual DNI of 2000 kWh/m^2 that uses biomass and a parabolic trough collector (PTC). Three examples of 10 MW power plants were examined in the study: a CSP power plant, a biomass power plant, and a hybrid CSP–biogas power plant. The LCOE for the three systems was 0.239, 0.116, and 0.154 EUR/kWh, respectively.

The hybrid system has a higher investment cost than CSP or biomass power plants. Additionally, it demonstrates that the hybrid system produces nearly 2.7 times as much energy as the CSP plant, meaning that the hybrid power plant has a lower LCOE (64%) than the CSP plant. Altayib and Dincer [14] examined a hybrid system in Saudi Arabia that used renewable energy sources—biomass and solar thermal—while producing electricity, heating, and fresh water. The findings demonstrated that conventional solar thermal storage can be removed, significantly boosting the solar thermal energy resource's economic competitiveness. Cogeneration allows for a maximum energy efficiency of 52%, while the maximum exergy efficiency is 47%. Nami et al. [15] evaluated a biomass-based tri-generation system with solar assistance to satisfy domestic energy needs. In addition to providing 1 MW_{el} of power, the results demonstrated that the intended system could supply 1241 kW of space heating, 101.5 kW of domestic hot water, and 55.35 kW of chilled water for space cooling. Ahmed and Mahanta [16] researched a 1 kW power-producing system that combines parabolic solar collectors and biomass furnaces. The scientists suggest that such a system might be used in rural agricultural areas with a plentiful supply of rice husks and enough open space for solar collectors.

According to a study by Liu et al. [17], the most effective system combinations featured CSP and at least one PV system. Kaur and Dhingra [18] presented the techno-economic feasibility of a solar biomass system in Ludhiana district of Punjab, India. The proposed system comprises a 1000 kW biomass power plant and a 100 kW PV plant. Finally, a global review [19] found that hybrid renewable energy systems, including solar thermal, have the potential to achieve competitive LCOE values ranging from USD 80 to USD 120/MWh, depending on regional resource quality, system size, and financing conditions.

In conclusion, the literature indicates a trend toward reducing the LCOE for hybrid solar thermal power plants through innovative designs, technology integration, and strategic policy support. Continued research is essential to refine cost estimates and develop best practices for implementing these systems in diverse geographic and economic contexts.

3. Methodology

The Greenius 4.9.0.1 program does not directly model hybrid power plants; instead, the modeling of the hybrid power plants is accomplished by considering them as pure solar plants with variable thermal storage. Then, the cost of biofuel production is considered to obtain the total cost and annual electricity production. This approach was conducted as follows:

Using the modeling program Greenius 4.9.0.1 to obtain the net cost of solar electricity at different FLHs from 1 to 10 at one-hour intervals and variable solar multiple factors (SM) from 1 to 8 at 0.5 intervals, resulting in 88 modeling operations.

The LCOE generated from biogas relies on global standards and references without accounting for the cost of the raw material.

The steam calculations application [20] was used to obtain the parameters of the thermodynamic cycle and their changes with varying condensation temperatures.

Using the practical experiment's results, an Excel spreadsheet was created to record data and simulate equations for the hybrid power plant (solar–biogas) at condensation temperatures.

The LCOE in the Greenius 4.9.0.1 application is calculated according to the following formula [21]:

$$\mathrm{LCOE} = \frac{(\mathrm{C_{inv}} + \mathrm{C_{o,m}} + \mathrm{C_{fuel}} + \mathrm{C_{tax}})\cdot \mathrm{crf}}{\mathrm{E_{net}}} \quad (1)$$

$$\mathrm{crf} = \frac{\mathrm{d}\cdot(1+\mathrm{d})^{\mathrm{n}}}{(1+\mathrm{d})^{\mathrm{n}} - 1}$$

This represents the capital recovery factor (crf) used in finance to calculate the annual payment required to recover an investment over a specified period.

Where:

LCOE: Levelized Cost of Energy (EUR/kWh);

C_{inv}: investment cost (EUR);

$C_{o,m}$: annual operating and maintenance cost (EUR);

C_{fuel}: annual fuel cost (EUR);

C_{tax}: annual taxes (EUR);

E_{net}: annual net electrical energy produced (kWh_{el});

crf: capital recovery factor;

d: annual interest rate (%);

n: lifespan of the station in years.

The cost of producing biogas is calculated based on the gas produced according to the following relationship:

$$C_{el,biogas} = \frac{C_{el,biogas,st}}{F_{inc,biogas}} \quad (2)$$

where:

$C_{el,biogas}$: LCOE generated from biogas (EUR/kWh);

$C_{el,biogas,st}$: reference cost of biogas production (should be calculated for the case);

$F_{inc,biogas}$: factor of increase in biogas production.

3.1. The Basic General Specifications for the Proposed Station

After determining the geographical location of the proposed station site, site parameters were obtained from the Greenius 4.9.0.1 application, which uses the climate file imported via Meteonorm 8, providing a global climate database [22]. Table 2 shows the site specifications for the proposed hybrid station.

Table 2. Specifications of the site for the proposed hybrid station.

Location (Idlib, Syria)	-	35.9° N, 36.6° E
Sea level	m	468
Minimum temperature (t_{min})	°C	6.3
Maximum temperature (t_{max})	°C	29.8
Annual average of temp (t_{ave})	°	18.2
Direct normal irradiation	kWh/m^2·year	2001

3.2. Energy Sources for the Hybrid Power Plant

There are two sources of renewable energy to operate the power plant:

Solar thermal energy: through a solar field (SF) of solar PTC, which uses thermal oil as a medium for heat transfer. Specifications of the field from the Greenius 4.9.0.1 program are shown in Table 3;

Table 3. Specifications of the solar field for the hybrid station design.

Solar Collector	SL 4600 PTR70 2009	-
Collector length (L)	120	m
Aperture width (w)	4.6	m
Number of rows/loops	26	-
Number of collectors in each row	4	-
Distance between rows	11	m
Distance between the collectors	3.5	m
Effective mirror of the receiver (A_c)	529	m^2
Nominal SF area ($A_{s.f}$)	55,016	m^2
Nominal optical efficiency of the collector (η_o)	73.3	%
Reference designing direct solar irradiation intensity (E_d)	800	W/m^2
Thermal production of solar field (at design direct solar radiation intensity and temperature 25 °C)	28,687	kW_{th}

Table 3. *Cont.*

The thermal medium used (thermal oil)	(Therminol VP-1)	-
Track the sun angle	North–South	-
Thermal oil inlet temperature to the SF ($t_{sf,in}$)	295	°C
Thermal oil outlet temperature from the SF ($t_{sf,out}$)	385	°C

Biogas energy: through a plant producing biogas based on the anaerobic digestion of the city's food waste and sewage sludge.

Assuming the plant operates at full capacity throughout the year, the biogas station compensates for the shortfall in supplying the SF.

For the biogas station to operate the power generation unit without solar energy, it must have a capacity equivalent to the SF. Therefore, as the SF's thermal capacity is 28,324 kWh_{th} (see Table 3), it should choose a burner with a capacity of 29 MW_{th}.

Power Block: a steam turbine is connected to an electric generator to obtain helpful energy. The suggested capacity of the turbine was 10 MW_{el}, with a capacity of P_{el} = 9987 kW_{el}.

The steam required to operate the steam turbine is obtained from the SF through a medium, thermal oil via heat exchangers (thermal oil–water) or a biogas burner (the auxiliary boiler). The Greenius 4.9.0.1 program contains several ready-made models for power generation units, from which the designer can choose one and adjust the output and capacity as needed. Depending on the steam calculation software and the Greenius modulation software, the generation unit (Solar Energy and Grid Storage-Standard) was chosen with a capacity of 34.2 MW_{el}, an efficiency of 35.3%, and an appropriate scale factor of 29.2%. Based on the modeling program Greenius and the steam turbine calculation program, the parameters of the power generation unit are as in Table 4.

Table 4. Parameters of the nominal power generation unit for the hybrid station.

Generator Capacity (P_{el})	9987	kW_{el}
The total nominal output of the thermodynamic cycle ($\eta_{c,tot}$)	35.3	%
The nominal thermal capacity input ($P_{t,in}$)	28.324	kWh_{th}
The steam inlet temperature for the steam turbine (t_{in})	370	°C
The temperature at the turbine outlet (condensation temperature (t_{out}))	41.5	°C
The inlet pressure for the turbine (absolute) ($P_{in,abs}$)	100	bar
Exit pressure from the turbine (absolute condensation pressure) ($P_{out,abs}$)	0.08	bar

The production of biogas increases with rising temperatures across various temperature ranges. To achieve this, it was suggested that condensation heat from the steam turbine condenser be utilized to raise the temperature of the digester by using heat exchangers, such as steam water and water slurry, in the condenser. This means that the condensation temperature must be higher than that of cooling water (between 11 °C and 17 °C is accepted [23]), and the temperature of cooling water is higher than the slurry, so the total difference between condensing temperature and slurry temperature is considered to be 20 °C.

On the other hand, the yield of the steam turbine cycle decreases with an increase in the condensation temperature, so the plant's overall performance must be studied. Two factors cause opposing results: an increase in the condensation temperature reduces the yield of the thermodynamic cycle and increases the production of biogas (within specific ranges). To verify this, the author conducted an experiment to produce biogas from identical organic samples in five identical test digesters, differing only in temperature.

4. Description of the Experiment

The experiment consists of five identical ADs, insulated metal cylinders (cylinders used for filling household gas) equipped with openings, as shown in Figure 1a.

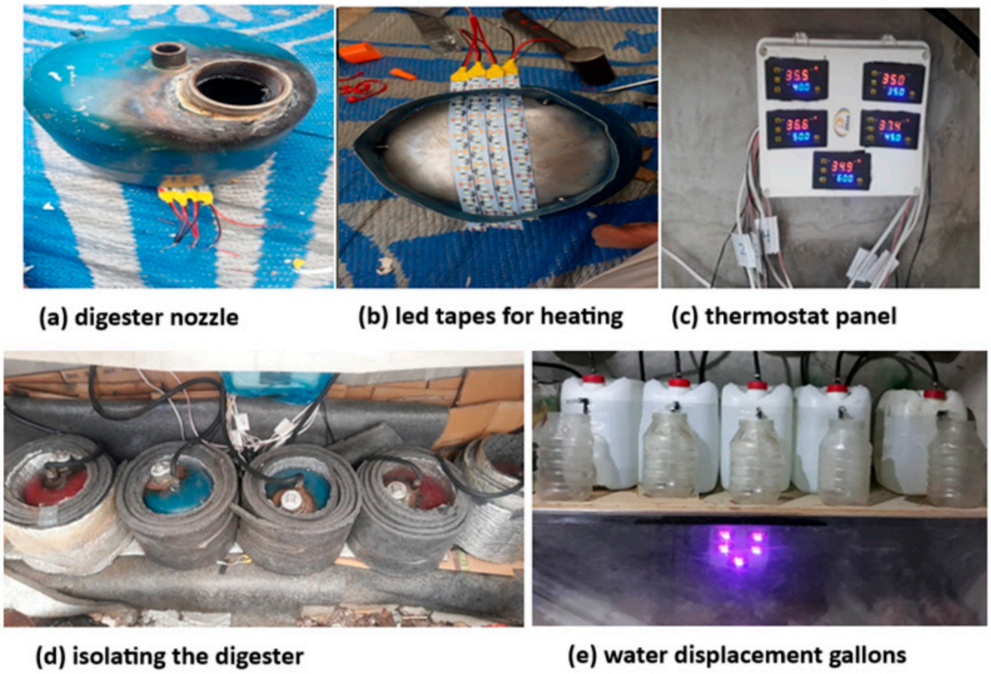

Figure 1. Experiment of biogas production from five batch digesters at different temperatures.

The five digesters were thermally insulated with reflective foam rolls (Figure 1d) and equipped with electric heaters (12-volt LED strips) (Figure 1b), temperature control devices (thermostats) (Figure 1c), and a temperature sensor for each digester in the center of the substrate. The water displacement method was used to measure the volume of the produced biogas. The tube coming out of the digester is connected to the top of plastic gallons (25 L capacity), and a tube is connected to the bottom of the plastic tank to collect water in containers (Figure 1e). The weight of the water in kilograms represents the volume of the gas released in liters. The organic material used was kitchen food waste (leftover cooked rice and bulgur, potatoes, eggplant, and stale bread) at 6.5 kg, fresh human waste (toilet waste) at 1.5 kg, and fermentation inoculum (water from a previous digester with cow manure) at 2.5 kg.

Each digester was filled with about 2 kg of the mixture, which consisted mainly of food waste (about 81%) and toilet waste (about 19%).

The temperatures were set according to five values: 55, 50, 45, 40, and 35 °C. Temperature measurements for the five digesters were taken six times a day (every four hours) to achieve the best possible accuracy, and the average temperature for each digester was recorded. The results were as follows: 49.6, 45.9, 43.5, 37.5, and 33.2 °C. The daily amount of gas released was calculated based on the weight of the displaced water for each digester. The experiment was put into service on 12 September 2022 and ended on 10 November 2022. The data were recorded in a programmed Excel spreadsheet containing the modeling results from the Greenius 4.9.0.1 and steam calculations programs, and the mathematical equations used to obtain the results and the graphs. The results of the experiment are shown in Table 5.

Table 5. Results of the five digesters over 60 days of the experiment.

Digestor Number	Temperature Set (°C)	Actual Average Temperature (°C)	Cumulative Biogas Yield (L)	Relative Increase Factor in Biogas Production
1	35	33.8	6.98	1
2	40	38.2	12.82	1.84
3	45	44	32.51	4.66
4	50	46.5	1.96	0.28
5	55	52	12.46	1.79

The methanogenic process that produces biogas functions according to several thermal fields [24] as illustrated in Figure 2:

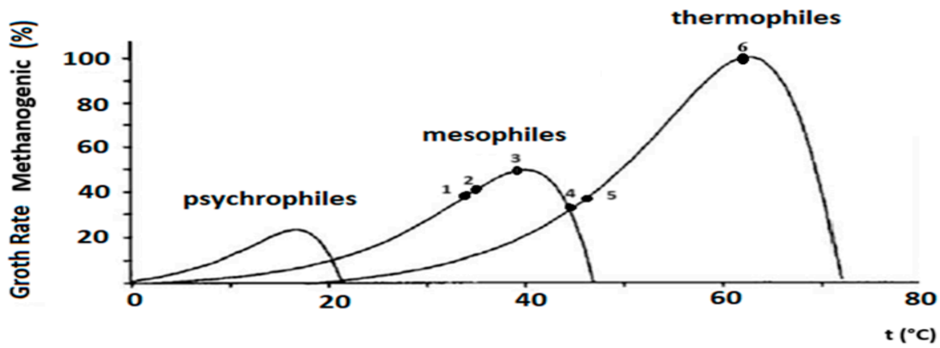

Figure 2. Ranges of growth for biogas-producing methanogenic bacteria and points of action for the experiment [24].

Psychrophile bacteria, the temperature range is between 10 and 20 °C;
Mesophiles bacteria, the temperature range is between 20 and 40 °C;
Thermophiles bacteria, the temperature range is between 50 and 65 °C.

Of course, these values are approximate and may vary from one reference to another. The most typical range is the second one, where mesophilic bacteria thrive.

By reading the actual average temperatures while considering the thermal gradient occurring in the digester, where the sensor is placed in the middle of the liquid, the section close to the surface produces biogas at a higher temperature. In comparison, the surrounding section operates at a lower temperature due to the heat loss to the outer surroundings. By plotting the work points on the graph in Figure 2, we find that the first and second cases (points 1 and 2) fall within the range of moderate temperatures (20–40 °C) and below the ideal value for bacterial growth. The third point is the one that achieved the highest biogas production rate, representing the ideal value (37.5 °C) in this field. The fourth point, representing the fourth state, lies outside the average temperature range. The fifth point, which represents the fifth condition, is located at the beginning of the high-temperature range for bacterial growth and below the ideal value within this range. The decline in biogas production in cases 4 and 5 (points 4 and 5) compared to point 6 can represent a transitional area between the medium- and high-temperature ranges, as both have indicated; this is consistent with the results of Nie et al. [25] and Kim and Lee [26].

Since the amount of its composite materials is constant, naturally switching from one operating temperature range to another does not increase the overall amount of biogas generated. However, the particular operating cost of producing biogas and energy from the plant rises since the retention period varies. Consequently, the daily production of biogas from the plant fluctuates for the same flow of raw material. The digester's heating cost must be considered, too, and each station's ideal operating point should be chosen based on its parts and design specifications.

5. Estimation of the Available Energy and Biogas Costs

Based on standard measurements and information according to IEA [27], the calorific value of biogas $H_{Biogas} = 6.5\ kWh/m^3$ and the overall electrical efficiency $\eta_{el} = 30\%$. Considering Idlib's population is one million, and the average of biogas per person is $0.022\ m^3$, the approximate annual electrical production for Idlib City would be as follows:

$$E_{ww} = 0.022 \times 1{,}000{,}000 \times 6.5 \times 0.3 \times \frac{365}{1000} = 15{,}658.5\ MWh_{el}/year \tag{3}$$

However, the municipal waste contains organic materials at a rate of 47.4%, and thus, each ton can produce approximately 81 kWh_{el} of electrical energy [28], which means the following for the city of Idlib:

$$E_{msw,c} = 81 \times 260 \times \frac{365}{1000} = 7668.9\ MWh_{el}/year$$

The total annual production available for the city of Idlib from sewage and municipal waste is as follows:

$$E_{ww,msw,c} = 15658.5 + 7668.9 = 23{,}327.4\ MWh_{el}/year$$

Throughout the Idlib governorate, approximately 1000 tons of municipal waste are produced daily [29], which could generate annual electrical energy as follows:

$$E_{msw,g} = 81 \times 1000 \times \frac{365}{1000} = 29{,}565\ MWh_{el}/year$$

However, the cost of transporting this waste (740 tons) from relatively distant areas to the station must be considered, which adds additional expense to the basic cost. The total electrical production for the Idlib area (sewage for the city of Idlib + municipal waste for the Idlib area) is as follows:

$$E_{ww,msw,g} = 15{,}658.5 + 29{,}565 = 45{,}223.5\ MWh_{el}/year$$

Biogas costs vary depending on the technology used and the plant's location. According to the global energy report on biomethane and biogas published in 2022 [30] (prices recorded for 2018), the following is derived:

For the digesters relying on sewage treatment plants: USD/MBtu 14.6 distributed as follows: USD/MBtu 4.3 for maintenance and operation; USD/MBtu 10.3 for construction cost. In terms of percentage, approximately 30% is spent on maintenance and operation and 70% on construction costs. For large digesters: USD/MBtu 9.3 (USD/MBtu 4.1 for maintenance and operation; USD/MBtu 5.2 for construction costs), with percentages of 44% for maintenance and operation and 56% for construction costs.

With an operating ratio of 19% for the wastewater treatment plant based on sewage waste and 81% based on organic municipal waste the following is derived:

The expected cost is $C_{biogas} = 0.19 \times 14.6 + 0.81 \times 9.3 = 10.307$ USD/MBtu;

It is distributed as follows:

Construction cost: $C_{biogas,inv} = 10.307 - 4.138 = 6.139$ USD/MBtu;

Maintenance and operation: $C_{biogas,o\&m} = 0.19 \times 4.3 + 0.81 \times 4.1 = 4.138$ USD/MBtu.

Regarding percentages, approximately 60% are construction costs and 40% are maintenance and operating costs.

Greenius 4.9.0.1 relies on the EUR in its computations; thus, all pricing should also be in EUR.

The cost in EUR is as follows: $C_{biogas} = 10.89 \times 0.828 = 9$ EUR/MBtu;

The overall energy yield is $\eta_{total} = \eta_{cycle} \times \eta_{boiler} = 0.35 \times 0.9 = 0.315$ (according to the Greenius modeling program), where:

The cycle efficiency (η_{cycle} = 0.35) is the thermodynamic cycle efficiency, and the boiler efficiency η_{boiler} = 0.9.

Consequently, taking into consideration that 1 MBtu = 293 kWh, the net cost of electricity is as follows:

$$C_{el,biogas,total} = 9/0.315 = 28.57 \text{ EUR/MBtu} = 0.0975 \text{ EUR/kWh}.$$

The cost is divided into the following:

Investment cost: $C_{el,biogas,inv}$ = 0.60 × 0.0975 = 0.0585 EUR/kWh;

Maintenance and operation: $C_{el,biogas,o\&m}$ = 0.40 × 0.0975 = 0.039 EUR/kWh.

In the Idlib area, 260 tons of municipal waste are available daily from the city at no transportation cost, and 740 tons need to be transported from distances outside the city limits. This adds cost to the biogas and, consequently, the electricity generated. Considering the average estimated cost of transporting organic waste in the Idlib area is 10 EUR per ton of raw municipal waste, the cost of producing electricity from sewage and municipal waste becomes the following:

$$C_{el,biogas,total} = 0.0975 + 10 \times 740 \times 365/45223500 = 0.157 \text{ EUR/kWh}$$

According to the International Renewable Energy Agency [31] and Lemonde [32], doubling the capacity of a biogas plant reduces investment costs by about 15% and maintenance and operational costs by approximately 15%. Based on the scenario mentioned above and depending on the volume of generated biogas, these figures were used to determine the variable cost of biogas.

Modeling operations were conducted by varying the SM from 1 to 8, with an interval of 0.5, and by changing FLHs from 0 to 10 h, with an interval of 1 h, resulting in 88 modeling operations in total.

6. Modeling and Simulation Results

6.1. Net Solar Power Plant (Without Biogas)

Figures 3 and 4 show the annual net electricity production and the LCOE generated by the solar power plant, respectively, along with the changes in SM at different FLHs for case 6. Figures 3 and 4 show the following: the most significant annual solar electricity production is achieved at SM = 8 and FLHs = 10 h, where $E_{solar,net}$ = 48.66 GWh_{el}, and the LCOE = 0.2896 EUR/kWh. The lowest cost for produced solar electricity is achieved at SM = 2 and FLHs = 5 h, which amounts to LCOE = 0.1781 EUR/kWh, and the annual electricity production is $E_{solar,net}$ 25.21 GWh_{el}. To achieve the maximum possible output from the solar plant (48.66 GWh_{el}), the cost of the produced electricity increases by approximately 61% from the minimum value, almost equivalent to doubling the output compared to the minimum cost scenario.

6.2. Hybrid Power Plant (Solar–Biogas) While Heating the AD with Condensation Heat

When the condensation temperature increases to achieve a higher temperature for the AD to boost biogas production, the efficiency of the thermodynamic cycle decreases, and energy production theoretically declines. However, biogas production increases, meaning that the Hydraulic Retention Time decreases, reducing biogas costs. Based on the steam calculations application [20], Table 6 illustrates the theoretical annual electricity production and the new cost of the produced biogas to be used later for calculating the total electricity cost produced for the studied cases. It is worth noting that case 1 is the reference case for biogas LCOE.

Figures 5–9 illustrate the LCOE produced for the five studied cases (solar–biogas), where t_{AD}: average digester temperature °C, and t_c: corresponding condensation temperature °C. It was found that the lowest LCOE = 0.1283 EUR/kWh was achieved at SM = 1 and FLHs = 0.

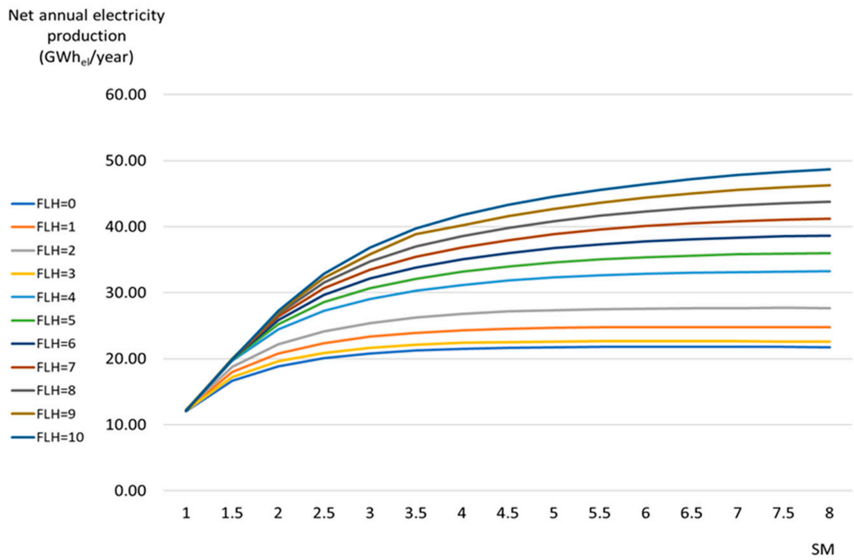

Figure 3. Annual net electricity generated by the solar plant, with variations in SM at different FLHs (storage capacities).

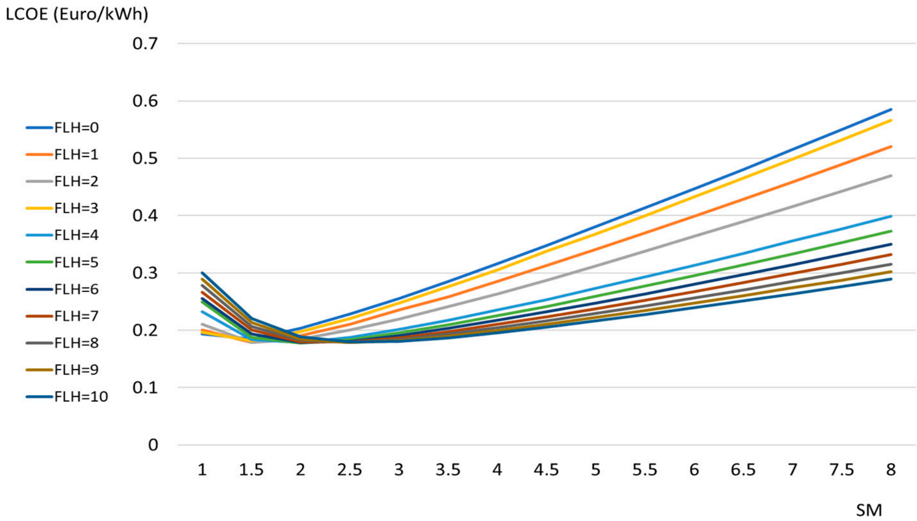

Figure 4. LCOE generated by the solar plant, with variations in SM at different FLHs (storage capacities).

Table 6. LCOE from biogas with changes in the digester temperature and the condensation temperature corresponding to the studied cases.

Case No	**1**	**2**	**3**	**4**	**5**
Average digester temperature, t_{AD} (°C)	33.17	37.5	43.52	45.87	49.6
Condensation temperature, t_c (°C)	41.5	57.5	63.5	66	70
Biogas production multiplier factor	1	1.84	4.66	0.28	1.79
The corresponding generator capacity (kW_{el})	9987	9210	8930	8810	8625
Total corresponding annual electrical energy produced (GWh_{el}/year)	87.48612	80.6796	78.2268	77.1756	75.555
LCOE biogas (EUR/kWh)	0.1615	0.1555	0.1283	0.1801	0.1667

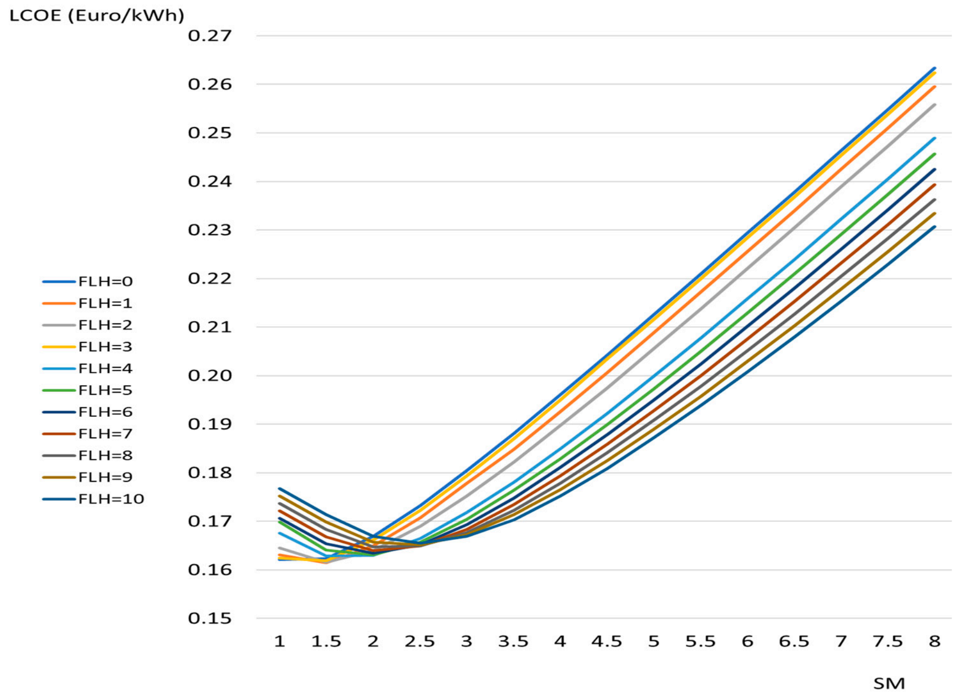

Figure 5. LCOE produced by the hybrid plant at different FLHs and SM for case 1 (reference) (t_{AD} = 33.17 °C; t_c = 41.5 °C).

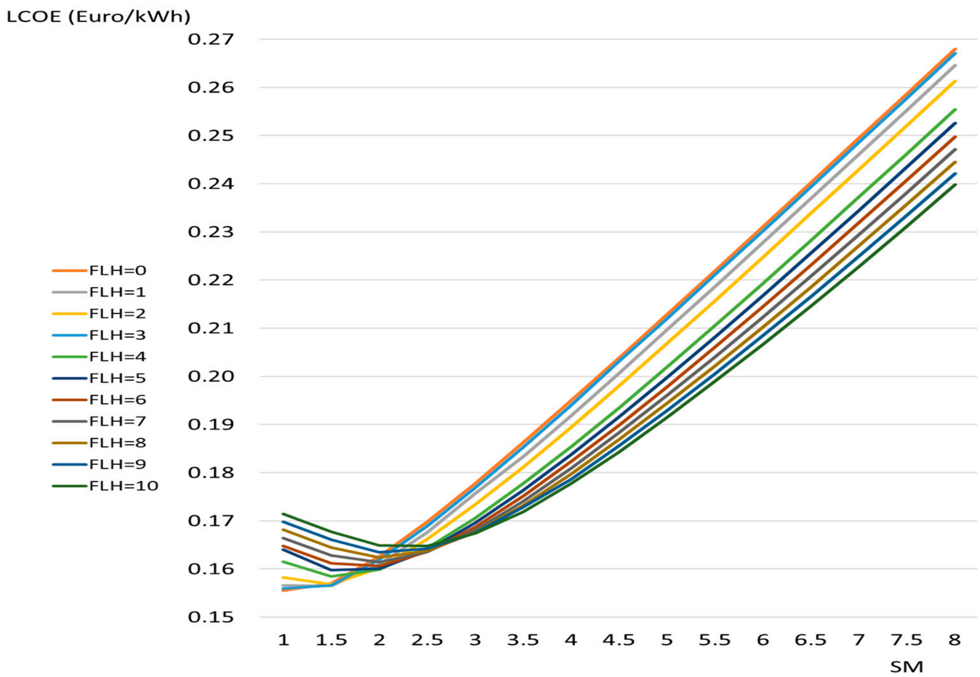

Figure 6. LCOE generated by the hybrid station for case 2 (t_{AD} = 37.5 °C; t_c = 57.5 °C).

By reading the figures, the following could be noticed:

For cases 1, 2, 4, and 5, the LCOE values are somewhat close, between 0.156 and 0.2 EUR/kWh for SM = 1; FLHs = from 1 to 10. This means that the hybrid power plant could produce electricity with a low LCOE and the possibility of storage for a few hours compared to solar nets.

The LCOE for case 3 (the best case) ranges from 0.1283 to 0.1447 EUR/kWh (SM = 1; FLHs = from 1 to 10). This enables the hybrid power plant to operate at sunset using solar storage heat with a low LCOE.

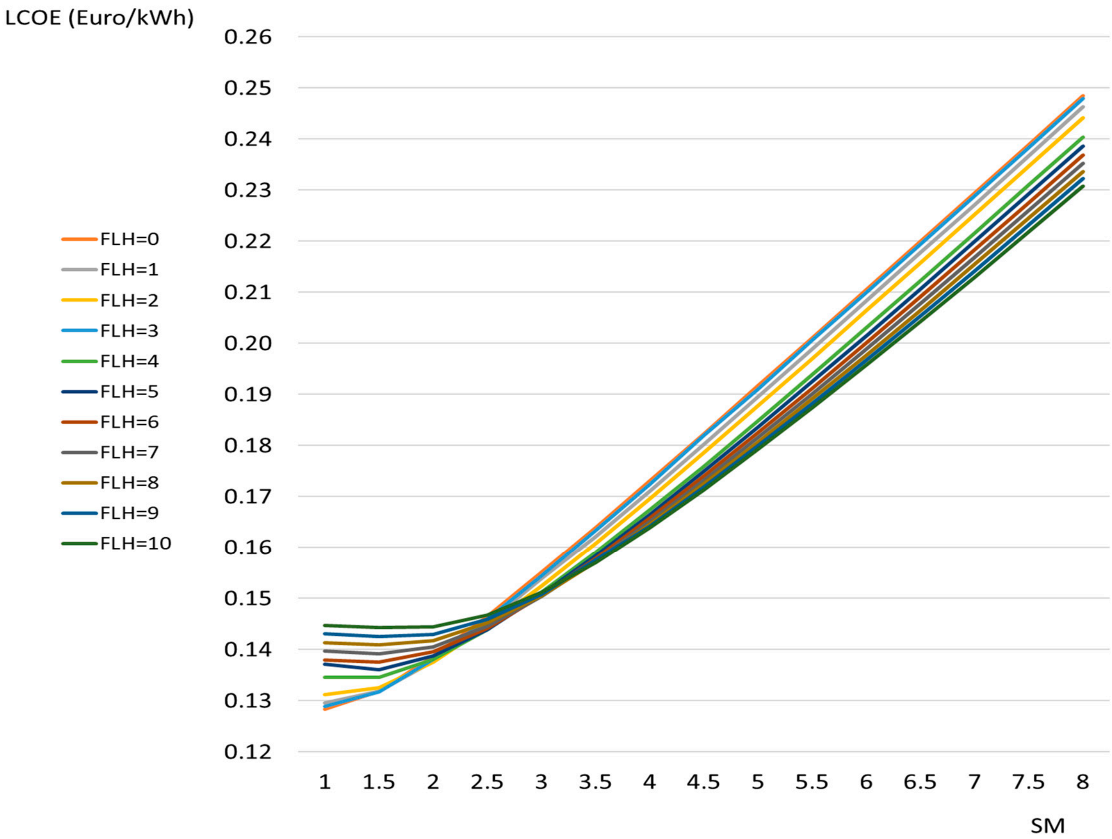

Figure 7. LCOE produced by the hybrid station for case 3 (t_{AD} = 43.52 °C; t_c = 63.5 °C).

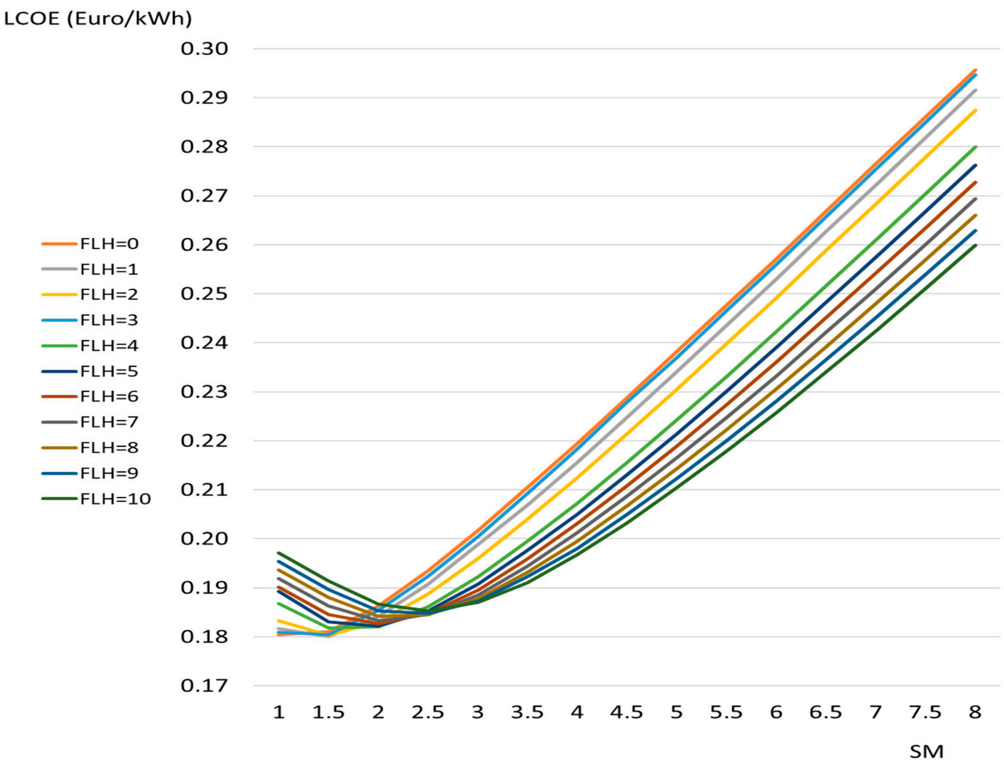

Figure 8. LCOE produced by the hybrid station for case 4 (t_{AD} = 45.87 °C; t_c = 65 °C).

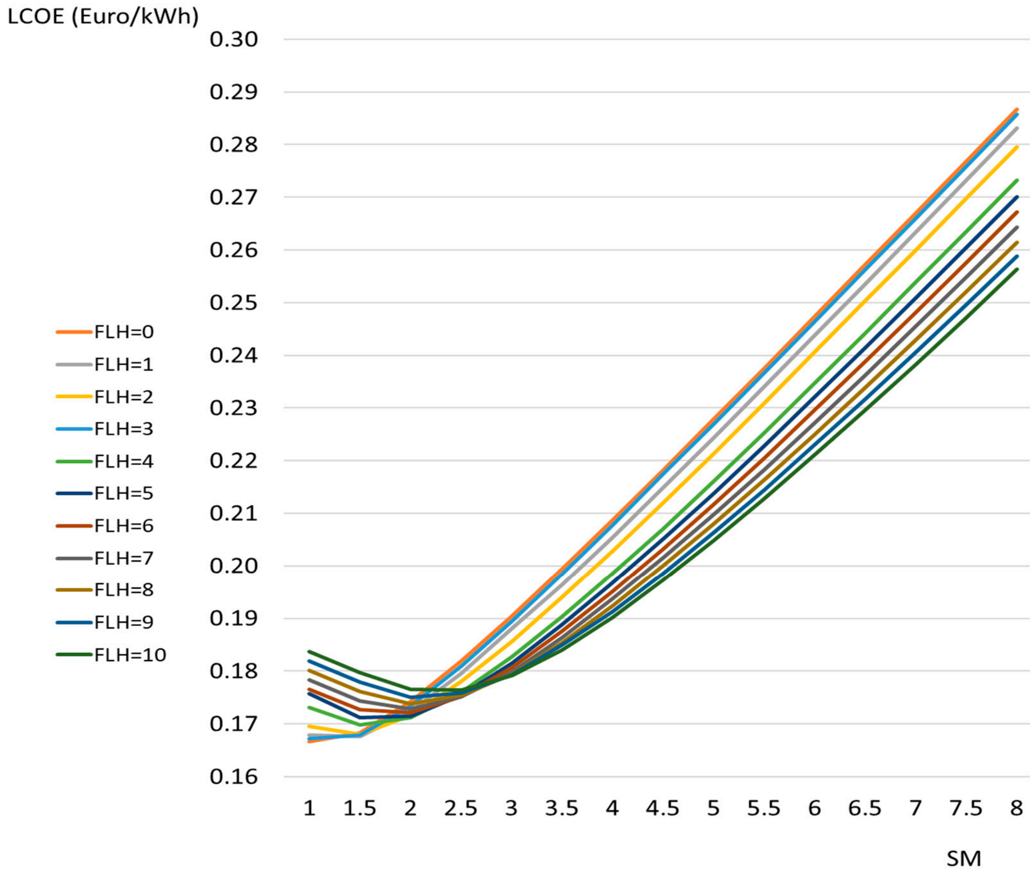

Figure 9. LCOE produced by the hybrid station for case 5 (t_{AD} = 49.6 °C; t_c = 70 °C).

In all cases, it is advised to operate the hybrid power plant with values of SM no greater than 2.5. This reduces the investment cost in the solar field and the area of land needed.

The hybrid solar–biogas system achieved a significant reduction in LCOE compared to pure solar energy or pure biogas energy, and at the same time, it achieved a competitive price compared to the prices of the electricity grid in Idlib [33].

6.3. Hybrid Power Plant with Heating the AD to the Optimal Temperature in the High-Temperature Range (Thermophilies)

Referring to Figure 2, it is clear that the optimal temperature for achieving the highest growth rate of gas-producing bacteria in the high range is approximately 62 °C, which results in a doubling of the growth of gas-producing bacteria. This requires a minimum condensation temperature of about 70 °C. Table 7 shows the projected annual production of electricity and LCOE for case 6. Figure 10 shows the LCOE produced according to SM at different FLHs; it is clear that the lowest LCOE = 0.0824 EUR/kWh was achieved at SM = 1 and FLHs = 0. Figure 10 shows that the optimal SM value for obtaining the lowest LCOE is SM = 1 for all FLH values, with the LCOE ranging from 0.0832 to 0.1004 EUR/kWh. This allows the hybrid power plant to function after sunset using solar storage heat, resulting in a reasonably low LCOE. Also, there is no pointed change in the LCOE at the same SM (if SM > 4) by changing the FLHs.

Table 7. Expected annual production and the cost of the generated electrical energy for case 6.

Case Number	6
The factor for doubling biogas production	9.32
The generator's corresponding capacity (kW_{el})	8165
The total corresponding annual electrical energy produced (GWh_{el}/year)	75.56
$LCOE_{biogas}$ (EUR/kWh)	0.0293

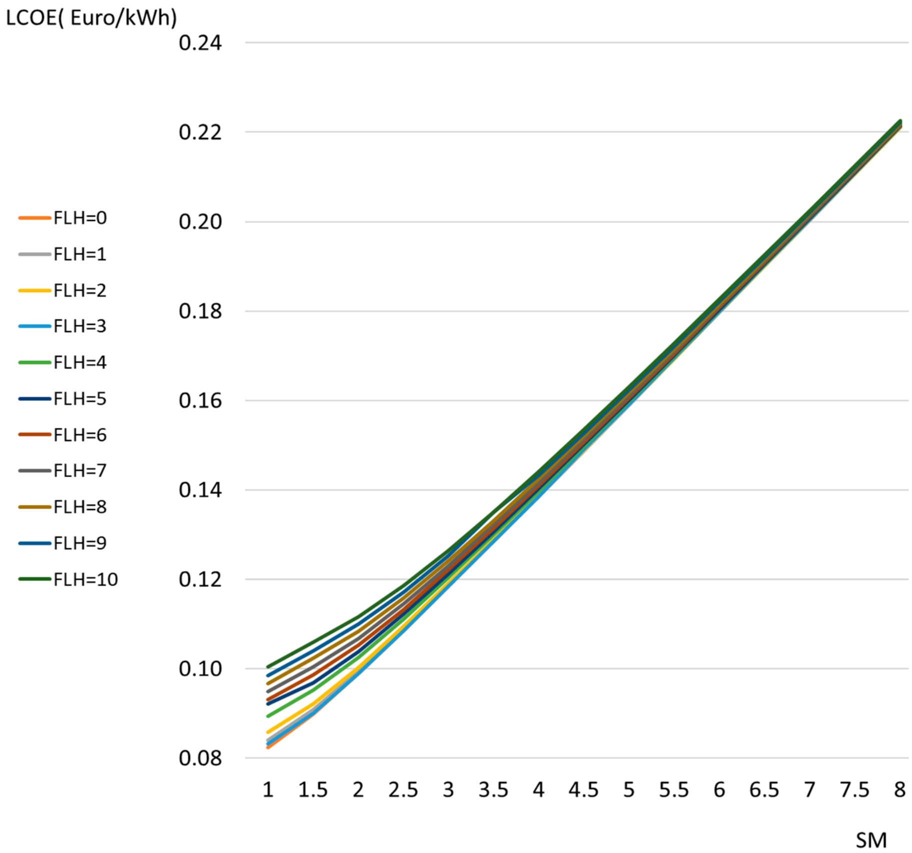

Figure 10. LCOE produced by the hybrid power plant for case six (t_{AD} = 62 °C; t_c = 80 °C).

7. Results and Discussion

In the case of operating as a pure solar station, the lowest value for the cost of produced electricity was LCOE = 0.1781 EUR/kWh, which was archived at SM = 2 and FLHs = 5, and the annual electricity production at that point was 25.21 GWh. However, the maximum annual electricity production was 48.66 GWh at FLHs = 10 h and SM = 8, and the annual LCOE = 0.2896 EUR/kWh. This means that to achieve the maximum annual electricity production, the LCOE increases by approximately 63% compared to the lowest LCOE. On the other hand, the annual electrical energy produced is approximately two-times higher than the production at the minimum LCOE. It can obtain annual electricity energy of about 80% approximately with an LCOE of less than 0.2 EUR/kWh at points SM $\geq$ 3.5 and FLHs $\geq$ 5. For example, the annual energy produced of 39.7 GWh at FLHs = 10 h and SM = 3.5, which is about 82% of the maximum possible annual production, is at an LCOE = 0.1864 EUR/kWh, which is less than 5% higher than the lowest possible LCOE.

When the system is a hybrid power plant, it can be found that the lowest LCOE produced was for case 3, amounting to LCOE = 0.1283 EUR/kWh, which meets FLHs = 0 h and SM = 1. When working at high temperatures (case 6), the minimum LCOE is 0.0824 EUR/kWh at FLHs = 0 h and SM = 1. The expected cost of the produced electricity will decrease to about 64% of case 3, which is the lowest. However, this option is unsuitable because methanogens are unstable at this temperature range. Table 8 highlights the key findings of the hybrid power plant in consideration of the following operation cases: biogas net, solar net, and hybrid. The generator capacity is the same in all cases. In the solar net instance, the power plant could create two values of yearly energy output, which naturally resulted in two values for the power factor, annual efficiency, and LCOE. Increasing yearly energy output by about 57.5% results in a 4.6 percent increase in the LCOE. Table 9 compares LCOE values for various hybrid solar–biogas power plants worldwide. The table shows that the LCOE ranged between 0.065 and 0.27 EUR/kWh. Of course, this variation is due to the difference in climatic conditions, solar and gas energy percentage in the systems, and the nominal and technical capacity used.

Table 8. Key findings of the hybrid power plant in consideration of operation cases (biogas–solar-hybrid).

Operation Case	Biogas Net	Solar Net (CSP)	Hybrid (CSP + Biogas)
Rated Net Capacity (kW_{el})	9987	9987	9987
Annul Energy production (GWh_{el})	45.22	25.21/39.70	87.48
Annual Power Factor	0.5	0.29/0.45	1
Annual Electrical Efficiency (%)	30	11/10	20
Solar Share (%)	0	100	14
LCOE (EUR/MWh)	157.0	178.1/186.4	128.3

Table 9. LCOE for CSP–biomass hybrid power plant for various locations.

Location	Reference	Hybrid Proposal	DNI (kWh/Year)	Nominal Capacity (MW)	LCOE (EUR/kWh)
Tunis	Soares et al. [34]	CSP–Biomass	1922	1 electricity/CHP	0.175/0.126
Messaad, Algeria	Pedrazzi et al. [35]	CSP–Biomass	2630	5	0.097
Madrid, Spain	Servert et al. [13]	CSP–Biomass	2000	10	0.153
Natal, Brazil	Khosravi et al. [36]	CSP–Biomass + desalination	2200	100	0.065
Lleida, Spain	Mohaghegh et al. [37]	CSP–Biomass	1812	22.5	0.270

8. Conclusions

This study convincingly demonstrated the benefits of combining solar CSP and AD biogas production based on municipal solid waste (MSW) and wastewater treatment in the Idlib governorate. The application of this study can help secure a renewable energy source in addition to the following benefits: ensuring the stability of the electricity produced, disposing of the wastes in a clean, energy-producing way, producing biofertilizer, and creating new job opportunities for the local community. Modeling operations were conducted for each case of the studied cases practically, as well as for the case corresponding to the highest growth rate of methanogenic bacteria theoretically; the modeling processes were conducted at 11 different values of storage capacity from FLHs = 0 to 10 and by varying the SM from 1 to 8. This study showed that when operating as a net solar plant, the lowest value for the LCOE was 0.1785 EUR/kWh at FLHs = 5 and SM = 2, while the annual electricity production was 25.21 GWh. The maximum annual electricity production is 48.66 GWh, achieved at FLHs = 10 h and SM = 8, and the LCOE = 0.2896 EUR/kWh. It is possible to obtain an annual electrical energy production of 39.7 GWh, which is about 82% of the maximum possible annual production, at a cost of LCOE = 0.1864 EUR/kWh. The LCOE is 5% higher than the lowest possible cost in this case. When operating the system as a hybrid plant with an annual capacity factor of 1, it was discovered that the lowest value of energy produced was in the third scenario at $t_{AD} = 43.52$ °C and $t_c = 63.5$ °C), with FLHs = 0 h and SM = 1; the LCOE = 0.1283 EUR/kWh.

In the end, it can be concluded that the hybrid solar–biogas system significantly reduced electricity costs compared to pure solar energy or pure biogas energy only and achieved a competitive price compared to the prices of the electricity grid in Idlib.

Author Contributions: Methodology, A.F.A.; Software, A.A.K.A.; Validation, R.A.A.; Formal analysis, A.F.A.; Investigation, R.A.A.; Resources, A.A.K.A.; Data curation, A.A.K.A.; Writing—original draft, A.A.K.A. and A.F.A.; Writing—review & editing, R.A.A.; Supervision, R.A.A.; Funding acquisition, R.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The researchers would like to thank the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2024).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation and Symbol

AD	Anaerobic Digester
c	City
CHP	Combined Heat and Power
crf	Capital Recovery Factor
CSP	Concentrated Solar Power
d	Annual Interest Rate
DNI	Direct Normal Irradiation
FLH	Full Load Hours
g	Governorate
GWh	Giga Watt Hour
IEA	International Energy Agency
inv	Investment
kWh	Kilo Watt Hour
LCOE	Levelized Cost of Electricity
MBtu	Million British Thermal Unit
MJ	Mega Joule
msw	Municipal Solid Waste
n	The Lifespan of the Station in Years
O&M	Operation and Maintenance
PTC	Parabolic Trough Collector
PV	Photovoltaic
SF	Solar Field
SM	Solar Multiple Factor
ST	Solar Tower
t_{ad}	Temperature of Digester
t_c	Temperature of Condensing
WW	Wastewater

References

1. Alhijazi, A.A.K.; Alloush, A.F. A review of renewable hybrid power plant technologies: A concept for improving the performance of hybrid solar-biogas power plants. *Int. J. Energy Technol. Policy* **2024**, *19*, 231–260. [CrossRef]
2. Alhijazi, A.A.K.; Almasri, R.A.; Alloush, A.F. A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review. *Sustainability* **2023**, *15*, 16803. [CrossRef]
3. Lipu, M.S.H.; Jamal, T. Techno-economic analysis of solar Concentrating power (CSP) in Bangladesh. *Int. J. Adv. Renew. Energy Res.* **2013**, *2*, 750–762.

4. Ministry of Local Administration and Services in Syria. 2024. Available online: https://hlp.syria-report.com/directory/minister-of-local-administration-and-services-ssg/ (accessed on 20 August 2024).
5. DEMAND, CLEAN POWER ON©. 2020 International Bank for Reconstruction and Development/CONCENTRATING SOLAR POWER. 2020 20-Feb-2024. Available online: https://www.nachhaltigwirtschaften.at/resources/iea_pdf/reports/iea_bioenergy_task37_wastewater_biogas_grey.pdf (accessed on 20 August 2024).
6. Waqar, M.; Shukla, A.K.; Sharma, M.; Maheswari, M.; Nandan, G. Review of Hybrid Solar-Biomass Power Generation System. *SAMRIDDHI A J. Phys. Sci. Eng. Technol.* **2022**, *14*, 348–358. [CrossRef]
7. Power, C.S. *Clean Power on Demand 24/7*; World Bank: Washington, DC, USA, 2021.
8. Thiam, A.; Mbow, C.; Faye, M.; Stouffs, P.; Azilinon, D. Assessment of hybrid concentrated solar power-biomass plant generation Potential in Sahel: Case study of Senegal. *Nat. Resour.* **2017**, *8*, 531–547. [CrossRef]
9. Peterseim, J.H.; White, S.; Tadros, A.; Hellwig, U. Concentrating solar power hybrid plants—Enabling cost effective synergies. *Renew. Energy* **2014**, *67*, 178–185. [CrossRef]
10. Ling, J.L.J.; Go, E.S.; Park, Y.-K.; Lee, S.H. Recent advances of hybrid solar—Biomass thermo-chemical conversion systems. *Chemosphere* **2022**, *290*, 133245. [CrossRef] [PubMed]
11. Coelho, B.; Oliveira, A.; Schwarzbözl, P.; Mendes, A. Biomass and central receiver system (CRS) hybridization: Integration of syngas/biogas on the atmospheric air volumetric CRS heat recovery steam generator duct burner. *Renew. Energy* **2015**, *75*, 665–674. [CrossRef]
12. Bai, Z.; Liu, Q.; Lei, J.; Wang, X.; Sun, J.; Jin, H. Thermodynamic evaluation of a novel solar-biomass hybrid power generation system. *Energy Convers. Manag.* **2017**, *142*, 296–306. [CrossRef]
13. Servert; Miguel, G.S.; Lopez, D. Hybrid solar-biomass plants for power generation; Technical and economic assessment. *Glob. NEST J.* **2011**, *13*, 266–276.
14. Altayib, K.; Dincer, I. Design and evaluation of a new solar-biomass based energy system for a small sustainable residential community. *J. Clean. Prod.* **2022**, *369*, 133275. [CrossRef]
15. Nami, H.; Anvari-Moghaddam, A.; Nemati, A. Modeling and analysis of a solar boosted biomass-driven combined cooling, heating and power plant for domestic applications. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101326. [CrossRef]
16. Ahmed, Z. Dimbendra Kr. Mahanta; Thermodynamics analysis of hybrid solar-biomass power generation system. *AIP Conf. Proc.* **2019**, *2091*, 020003. [CrossRef]
17. Liu, Q.; Bai, Z.; Wang, X.; Lei, J.; Jin, H. Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems. *Energy Convers. Manag.* **2016**, *122*, 252–262. [CrossRef]
18. Kaur; Gupta, S.; Dhingra, A. Analysis of hybrid solar biomass power plant for generation of electric power. *Mater. Today Proc.* **2022**, *48*, 1134–1140. [CrossRef]
19. Renewable Energy Statistics 2020. 2020. Available online: https://www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020 (accessed on 10 September 2024).
20. *The Turbine Steam-Consumption Calculator*; Version 2.4; Wayne Jayes & Harvey Wilson, 2013. Available online: https://www.katmarsoftware.com/turbine.htm (accessed on 10 September 2024).
21. Dersch, J.; Dieckmann, S. Greenius, Train, Retain and Manage Your Crews with These, 5 Easy Steps. The #1 Training Software for Landscapers. 2024. Available online: https://gogreenius.com/how-greenius-works/ (accessed on 20 May 2024).
22. Meteonorm V8.2.0.24079. 2024. Available online: https://meteonorm.com/en/ (accessed on 22 July 2024).
23. Typical Design Conditions for Steam Condensers. 2024. Available online: https://buildingcriteria2.tpub.com/ufc_3_540_02n/ufc_3_540_02n0129.htm (accessed on 12 August 2024).
24. Rashidian, P.; Mahmoudimehr, J.; Atashkari, K. An underground anaerobic digester with permissible temperature fluctuations: A parametric study. *Clean. Energy Syst.* **2022**, *2*, 100007. [CrossRef]
25. Nie, E.; He, P.; Zhang, H.; Hao, L.; Shao, L.; Lü, F. How does temperature regulate anaerobic digestion? *Renew. Sustain. Energy Rev.* **2021**, *150*, 111453. [CrossRef]
26. Kim, J.; Lee, C. Response of a continuous anaerobic digester to temperature transitions: A critical range for restructuring the microbial community structure and function. *Water Res.* **2016**, *89*, 241–251. [CrossRef] [PubMed]
27. Bachmann, N.; la Cour Jansen, J.; Bochmann, G.; Montpart, N. *Sustainable Biogas Production in Municipal Wastewater Treatment Plants*; IEA Bioenergy: Massongex, Switzerland, 2015; Volume 20.
28. BIOGAS CALCULATOR. 2024. Available online: https://www.renergon-biogas.com/en/biogas-calculator/ (accessed on 29 July 2024).
29. Bakkour, B.M.W. Studying The Factors Affecting the Efficiency of Energy Production from Processing Solid Wastes in Idlib Governorate in Mechanical Engineering. Ph.D. Thesis, Idlib University, Idlib, Syria, 2024.
30. Outlook, I. For biogas and biomethane: Prospects for organic growth. *World Energy Outlook Spec. Rep.* **2020**, *93*. Available online: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth (accessed on 11 September 2024).
31. IRENA. Biomethane. 2024. Available online: https://www.irena.org/Energy-Transition/Technology/Transportation-costs/Biomethane (accessed on 26 July 2024).
32. Lemonde, M. 10 Tips to Reduce the Costs of Your Biogas/RNG Plant and Increase Its Profitability. 2019. Available online: https://www.biogasworld.com/news/reduce-the-costs-of-biogas-plant/ (accessed on 25 July 2024).
33. Green Energy. 2024. Available online: https://greenenergysy.com/contact/ (accessed on 24 August 2024).

34. Soares, J.; Oliveira, A.C.; Dieckmann, S.; Krüger, D.; Orioli, F. Evaluation of the performance of hybrid CSP/biomass power plants. *Int. J. Low-Carbon Technol.* **2018**, *13*, 380–387. [CrossRef]
35. Pedrazzi, S.; Masetti, F.; Allesina, G.; Tartarini, P. Hybridization of solar power plants with biogas from anaerobic digestion: A modeled case study. In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2019.
36. Khosravi; Santasalo-Aarnio, A.; Syri, S. Optimal technology for a hybrid biomass/solar system for electricity generation and desalination in Brazil. *Energy* **2021**, *234*, 121309. [CrossRef]
37. Mohaghegh, M.R.; Heidari, M.; Tasnim, S.; Dutta, A.; Mahmud, S. Latest advances on hybrid solar–biomass power plants. *Energy Sources Part A Recovery Util. Environ. Eff.* **2021**, 1–24. [CrossRef]