A low-carbon multigeneration system based on a solar collector unit, a bio waste gasification process and a water harvesting unit

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Abstract

In this study, we introduce and examine a novel multigeneration cycle powered by low-carbon bio-waste and integrated with a solar thermal component. This system is designed to convert sewage sludge into a variety of useful products. The cycle utilizes anaerobic digestion and gasification to produce biogas and syngas. Additionally, it incorporates processes for generating water and hydrogen energy, utilizing the atmospheric water harvesting unit and water/gas shift reaction, sequentially. The system employs a Rankine cycle, a Brayton cycle and two organic Rankine cycles (ORCs) for electricity generation. A significant portion of the heat and electricity in this proposed project is sourced from a waste heat recovery system. This innovative project not only presents a new structure and configuration for product generation but also addresses energy, water and environmental challenges concurrently. The energy system's performance has been thoroughly assessed in terms of thermodynamics, environmental impact and economic feasibility. The proposed plant is capable of producing an estimated 17 920 kW of electric power, 3207.6 kg/h of hydrogen energy and 5.14×10^{-3} L/s of freshwater. Under these design conditions, the energy and exergy efficiencies of the system were determined to be 35.76% and 40.49%, respectively. Additionally, the exergy sustainability factor, the levelized total emitted carbon dioxide and the unit cost of total products were characterized to be 52.28%, 0.2145 kg per kWh and 0.05219 $ per kWh, respectively.

Keywords: low-carbon multigeneration; wastewater treatment; solar collector unit; bio waste gasification; water harvesting unit

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1. INTRODUCTION

In contemporary times, the rapid social and industrial advancements have made water and energy essential for societal needs. Energy security and sustainability are crucial for achieving sustainable development, as highlighted in various studies [1, 2]. Despite the Earth's vast coverage by seas and oceans, there are significant challenges and limitations in accessing clean, drinkable and industrially usable water resources [3, 4]. Simultaneously, the reliance on fossil fuels for a substantial portion of energy demands leads to severe environmental degradation [5]. Traditional energy systems often exhibit low energy conversion performance, resulting in significant wastage of recoverable energy. This not only harms environmental and human health but also

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diminishes theirs effectiveness and sustainability [6, 7]. Against this backdrop, industrial and municipal wastewater treatment emerges as a viable solution to the crisis of water resource shortages [8, 9]. Recently, integrated energy systems capable of producing multiple outputs have gained popularity [10, 11]. These systems can provide environmental and economic advantages while enhancing performance, whether implemented for distributed generation systems or plant-scales purposes [12, 13]. Studies indicate that the recovery of waste heat from different units can heighten energy production efficiency and lessen environmental impacts associated with waste discharge [14]. Moreover, employing wastewater treatment processes and waste energy recovery from these plants, as a form of biomass fuel, has been identified as an effective way to protect the environment via waste-to-energy conversion [15, 16]. Although multigeneration systems often rely on fossil fuels, their detrimental environmental impacts have led scientists to favor renewable and green energy sources [17]. Solar energy [18, 19] and biomass fuel, as renewable energy sources, are increasingly integrated into multigeneration systems, offering a promising solution [20–22]. Among various biomass sources, bio-waste, particularly sewage sludge exit wastewater treatment units, stands out as a valuable resource that does not compete with the food chain [23–25].

Water and electricity, as primary societal necessities, are desirable outputs of any multigeneration systems. Additionally, heating load from solar/biomass-based plants and hydrogen gas as a clean fuel are also valuable products of these systems [21, 26, 27]. Hydrogen production can stem from various processes, including biomass energy conversion, water electrolysis and reforming of fossil energies [28], with its environmental friendliness being enhanced when based on renewable sources [29]. Freshwater production through desalination is a newer solution to water scarcity, though it can be expensive for regions distant from seawater sources [24]. The atmospheric water harvesting unit (AWHU) has recently emerged as a cost-effective method for producing water for different purposes, especially when integrated with renewables such as biomass energy [30].

Assareh *et al.* [31] conducted a study focusing on the energy and exergy evaluations of a plant that harnesses both biomass and solar energies. The system was coupled with the hydrogen liquefaction and heat recovery units. Their findings showed the system's electricity and exergy efficiency to be ~7900 kW and 11%. In a separate study, Prieto *et al.* [32] devised a thermal model for a solar collectors and biomass boiler-powered greenhouse, incorporating an absorption chiller to adapt to both winter and summer conditions. Simulating this setup for a tomato crop in Mediterranean climates, they discovered the system's potential to yield ~26.3 kWh/m^2 for heating and 62 kWh/m^2 for cooling. Additionally, the solar fraction and biomass operational cost were estimated at about 55% and 2.7 €/m^2/year, respectively. Wang *et al.* [33] explored the integration of solar and biomass green energy sources, finding a potential reduction in carbon dioxide emissions by roughly 35%.

Chen *et al.* [34] developed a novel power generation system that utilized sewage sludge drying and incineration, where fuel was first dried utilizing steam (at low pressure) before incineration in a boiler, the output of which fed a steam turbine. Rulkens [35] highlighted that among the various approaches for managing sludge from municipal wastewater treatment plants, energy production stands out as a key strategy. The literature also indicates that organic Rankine cycles (ORCs) are gaining popularity in power generation, especially when coupled with the biomass-assisted units. Moreover, ORCs, capable of generating electric power through a common Rankine cycle utilizing a low-grade heat source, can be effectively employed as a heat recovery unit in bottoming processes [36].

A thorough review of existing literature reveals that there are very few studies on the concurrent utilizing of biogas and syngas generation processes via the sewage sludge's anaerobic digestion and subsequent gasification of digestate. In response to this gap, a new bio-waste-based multigeneration plant (BWMGP) that incorporates a solar farm is introduced under the generation of diverse products such as electric power, freshwater, heat and hydrogen gas. This proposed MGP harnesses syngas and biogas from gasification and anaerobic digestion units, sequentially. Moreover, the production of water and hydrogen energy involves the AWHU and water/gas shift reaction ones. Additionally, a significant portion of heating capacity and electricity is derived from a waste heat recovery system, contributing to environmental conservation by minimizing waste discharge. This project, therefore, not only introduces an innovative structure and configuration for generating useful products but also addresses a notable research gap in bio-waste-driven MGPs. Particularly, the coupling of the AWHU with BWMGPs has seldom been explored in previous research. Furthermore, the generation of green hydrogen via a BWMGP-based water/gas shift reaction presents a promising avenue for reducing environmental harm. The performance of this energy system has been extensively assessed from thermodynamic, financial and environmental perspectives.

2. METHODOLOGY

The envisioned BWMGP is designed to utilize sewage sludge, a form of bio-waste, as its primary input. This innovative project is not only geared toward the production of diverse products from sewage sludge but also aims at significantly mitigating environmental impacts that arise from the disposal of sewage sludge. Managing sewage sludge through such a system could lead to substantial savings for the organizations involved [37, 38].

As illustrated in Figure 1, the BWMGP's design incorporates an interconnection of various units. These include three distinct power generation cycles—the Rankine cycle (steam turbine, STurb), the Brayton cycle (gas turbine, GTurb), and the ORC that utilizes a STurb in conjunction with an organic stream. The Brayton cycle is fueled by the biogas produced, while the other two cycles utilize flue gas for power generation. It is important to note that the syngas and biogas essential for these processes are derived from gasification and digestion cycles. In addition to power generation, the BWMGP features cycles

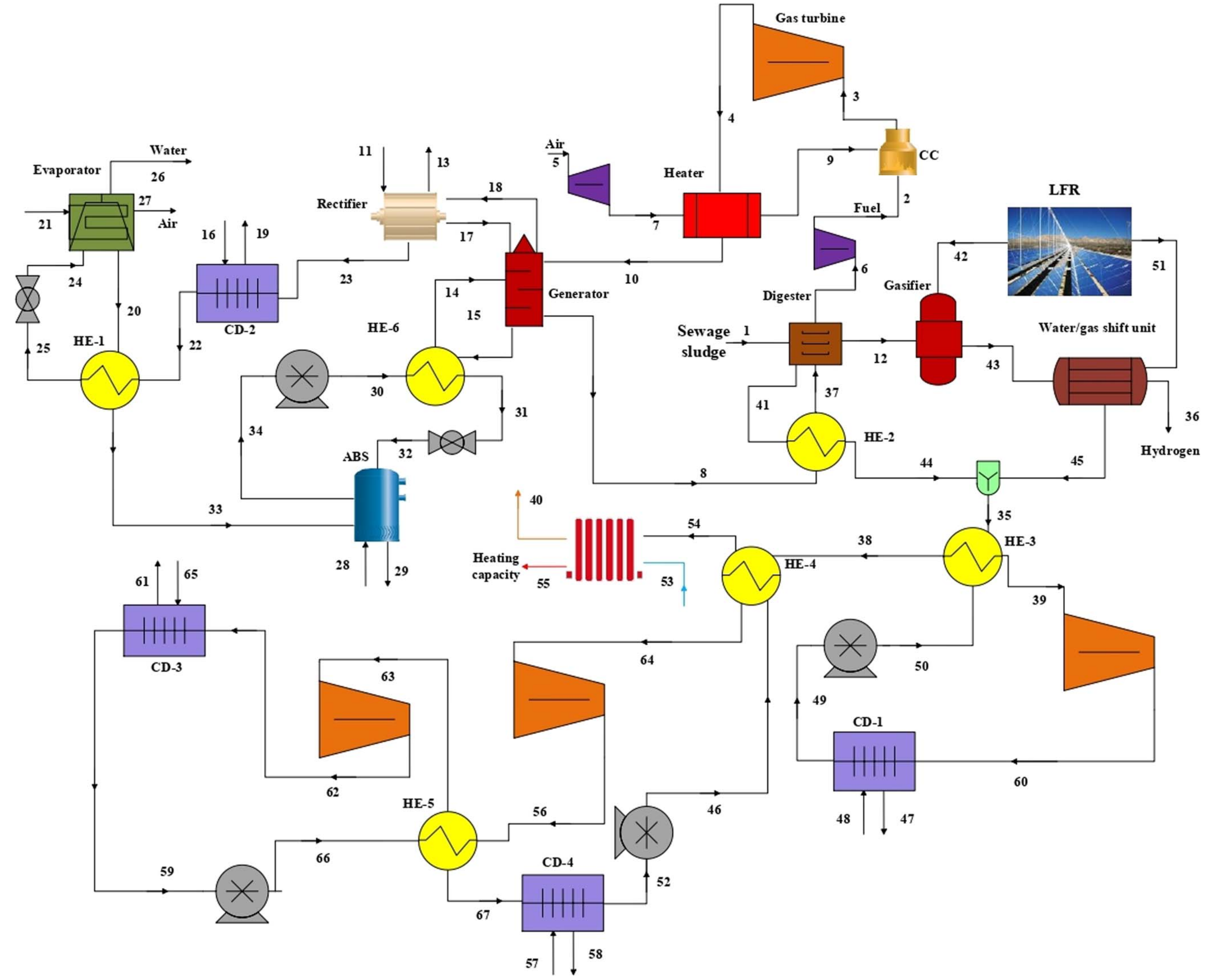


Figure 1. *The design and structure of the proposed BWMGP.*

for producing hydrogen energy and fresh water. The entire system of the BWMGP, including the intricate interplay of these various components, has been simulated using MATLAB and Aspen-HYSYS software, ensuring a comprehensive analysis of its functionality and efficiency. This research stands out due to its multifaceted approach, not only in terms of energy and resource generation but also in its potential to offer environmentally sustainable solutions for sewage sludge management, which is a growing concern in many parts of the world.

3. MATHEMATICAL MODELING

The mathematical model developed for this study is grounded in analyses of thermodynamics, exergoeconomics and environmental factors. Fundamental to the energy/exergy analysis are the first and second thermodynamics laws [39, 40]. These laws guide the formulation of mass/energy equilibriums (stemming from the first law) and the exergy equilibrium (derived from the second ones). For any designated control volume within the system, these critical relationships are established in accordance with the principles outlined in references [41, 42]

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{1}$$

$$\sum \dot{m}_i.h_i - \sum \dot{m}_o.h_o = \dot{W} - \dot{Q} \tag{2}$$

$$\sum \dot{E}_i + \dot{E}_q - \dot{E}_D = \sum \dot{E}_o + \dot{W}_{cw}. \tag{3}$$

In accordance with the energy equilibrium, the formulation for calculating the electricity produced by the STurb or GTurb and the pump's consumed power are as follows, as referenced

Table 1. *The proximate and ultimate assessments of the sewage sludge under consideration.*

Ultimate analysis (wt.%)					Proximate analysis (wt.%)		
H	C	N	O	S	MC	Ash	VM
4.50%	37.0%	3.30%	19.50%	0.65%	75.0%	30.0%	65.0%

MC: Moisture content, VM: Volatile matter.

in [43, 44]:

$$\dot{W}_{STrub/GTurb} = \dot{m}_i \times (h_i - h_o) \tag{4}$$

$$\dot{W}_{Pu} = \dot{m}_i \times (h_o - h_i)\,. \tag{5}$$

From an exergy perspective, the exergy flow of a given point includes kinetic, potential, chemical and physical components [45, 46]. However, for practical calculations, the kinetic and potential terms are often negligible. Therefore, the exergy of each stream is primarily calculated based on its chemical and physical attributes, as detailed in the following formulation [47]:

$$ex = ex_{ch} + ex_{ph}. \tag{6}$$

Furthermore, the total destroyed exergy of the offered BWMGP is [48, 49]

$$\dot{E}_{D,tot} = \sum \dot{E}_k. \tag{7}$$

The energy cycle in the study begins with the sewage sludge's digestion process from a Water Treatment Plant. Table 1 presents the proximate and ultimate assessments of the sewage sludge under consideration. Drawing from existing literature [50], the biogas captured during this process is assumed to be composed of 40% CO_2 and 60% CH_4. Based on this composition, the overall reaction for the sewage sludge's digestion is formulated as follows [51]:

$$\begin{aligned} C_aH_bO_c + (a - 0.25b - 0.5c)\ H_2O \rightarrow (0.5a + 0.125b \\ - 0.25c)\ CH_4 + (0.5a - 0.125b + 0.25c)\ CO_2 \end{aligned}\,. \tag{8}$$

The required thermal duty for the digestion cycle described is equated to the required thermal to raise the water temperature from the initial value to the required ones for the digestion cycle, as outlined in [52]

$$\dot{Q}_{DGC} = \dot{m} \times C_P \times (T_{DGC} - T_i)\,. \tag{9}$$

In this context, the subscript 'DGC' is used to denote the digestion cycle. Furthermore, '$\dot{m}$' represents the mass flow rate, while 'C_P' refers to the specific heat capacity of water [53].

Subsequent to the anaerobic digestion, the resultant by-product, known as digestate, is then processed in a gasifier to produce syngas. The overall reaction for this steam-based gasification process is described as follows [54]:

$$\begin{aligned} CH_aO_b + \omega H_2O + \alpha H_2O \rightarrow \\ \beta_1 H_2 + \beta_2 CO_2 + \beta_3 CO + \beta_4 CH_4 + \beta_5 H_2O. \end{aligned} \tag{10}$$

In this formulation, 'ω' signifies the moisture mole, and 'α' represents the mole of added steam, as detailed in [55]

$$\omega = \frac{MC \times M_{DG}}{18 - 18 \times MC}, \qquad R_{SB} = \frac{18 \times \alpha}{M_{DG} + 18 \times \omega}. \tag{11}$$

In the steam-assisted gasification cycle, an allothermal reaction occurs, where the necessary heat is provided by an external unit. Solar energy is a popular, abundant and clean resource [56]. Solar collectors produce the required steam by converting solar energy into heat [57]. For the plant in question, this external unit is a solar filed using linear Fresnel reflector (LFR). The primary energy input for these concentrating solar collectors is Direct Normal Irradiance [58]. To model the LFR, a 2D mathematical approach is employed to calculate the heat output for a single LFR. Based on this approach, the heat output rate of a LFR can be expressed through the following formulation, as detailed in references [36, 59]:

$$\dot{Q}_{LFR} = \dot{Q}_i - \dot{Q}_{l,p} - \dot{Q}_{l,f}. \tag{12}$$

The syngas obtained from the gasification process is initially routed to the Water/Gas Shift Heat Recovery unit (WGSHRU) for hydrogen production. In this unit, syngas undergoes a transformation into hydrogen gas via a gas/water shift reaction. This conversion cycle also requires thermal power, typically in the form of steam, which in this project is supplied by the solar farm. Additionally, the water produced by the AWHU can be calculated using the following equation [30]:

$$\dot{m}_{H_2O} = \left(R_{AH,25} - R_{AH,27}\right) \times \dot{m}_{dry-air}. \tag{13}$$

The net output power of the proposed BWMGP is

$$\dot{W}_{net} = \dot{W}_{BC} + \dot{W}_{RC} + \sum \dot{W}_{ORC} - \sum \dot{W}_{CP/Pu}. \tag{14}$$

Also, the thermodynamic efficiencies of the proposed BWMGP are expressed by

$$\eta_{EN} = \frac{\dot{W}_{net} + \dot{Q}_{Heating} + \left(\dot{m}_{H_2} \times LHV\right) + \left(\dot{m}_{FW}.h_{FW}\right)}{\left(\dot{m}_{DG} \times LHV_{DG}\right) + \dot{m}_{38}h_{38} + \dot{m}_{36}h_{36}} \tag{15}$$

$$\eta_{EX} = \frac{\dot{W}_{net} + \dot{E}_{50} + \dot{E}_{55} + \dot{E}_{H_2} + \dot{E}_{FW}}{\dot{m}_{DG} \times \dot{E}_{DG} + \dot{E}_{38} + \dot{E}_{36}}. \tag{16}$$

The LHV of sludge is 18 MJ/kg.

3.1. Exergoeconomic assessment

Exergoeconomic analysis, which integrates economic aspects with exergy analysis, is instrumental in unveiling the connection between the cost of products and thermodynamic inefficiencies. This analysis begins with the formulation of a cost balance equation, which can be expressed as follows [60–62]:

$$\dot{Z}_k = \sum \dot{C}_{o,k} - \dot{C}_{q,k} - \sum \dot{C}_{i,k} - \dot{C}_{w,k}. \tag{17}$$

Here, $\dot{Z}_k$ is the capital cost. Also, $\dot{C}$ denotes the cost rate, as formulated by [63]

$$\begin{cases} \dot{Z}_k = \frac{Z_k \times \phi \times \mathrm{CRF}}{N \times 3600}, \qquad \dot{C} = \dot{E}.c \\ \mathrm{CRF}: \text{Capital recovery factor} \rightarrow \mathrm{CRF} = \frac{i.(1+i)^n}{(1+i)^n - 1} \end{cases}. \tag{18}$$

Besides that, the total products unit cost of the proposed BWMGP is

$$TPCU = \frac{\dot{C}_W + \dot{C}_{42} + \dot{C}_{26} + \dot{C}_{50} + \dot{C}_{52}}{\dot{W}_{net} + \dot{E}_{42} + \dot{E}_{26} + \dot{E}_{50} + \dot{E}_{52}}. \tag{19}$$

Note that, the CO_2 unit damage cost and specific cost of heating were 0.024 \$/kg and 0.04 \$/kWh, respectively.

3.2. Environmental assessment

A primary motivation for establishing new BWMGPs, like the one proposed, is to lessen the environmental impacts associated with the use of fossil fuels. Consequently, these new systems are expected to demonstrate enhanced environmental performance [64]. A significant contributor to environmental pollution is carbon dioxide emissions [65, 66]. In the proposed BWMGP, carbon dioxide emissions primarily arise from the combustion of biomass energy. The Levelized Total CO_2 Emissions (LTE-CO_2) for this system can be estimated using the following method [67]:

$$LTE{-}CO_2 = \frac{\dot{m}_{CO_2}}{\dot{W}_{net} + \dot{Q}_{Heating} + \left(\dot{m}_{H_2} \times LHV_{H_2}\right) + \left(\dot{m}_{FW} h_{FW}\right)}. \tag{20}$$

4. RESULTS AND DISCUSSION

4.1. Model verification

As the proposed MGP introduces a unique process with an innovative structure and configuration for producing various useful products, it was essential to validate the models of different units individually. To this end, the performance of the conducted modelling for the BC was compared with outcomes found in existing literature, as shown in Table 2A. This comparison demonstrates a high level of accuracy in the simulation. Additionally, the conducted modelling for the gasification unit was compared with experimental outcomes, with findings listed in Table 2B. This comparison focused on the overall concentrations of syngas constituents. The results of these comparisons affirm the reliability and validity of the simulations conducted for the system.

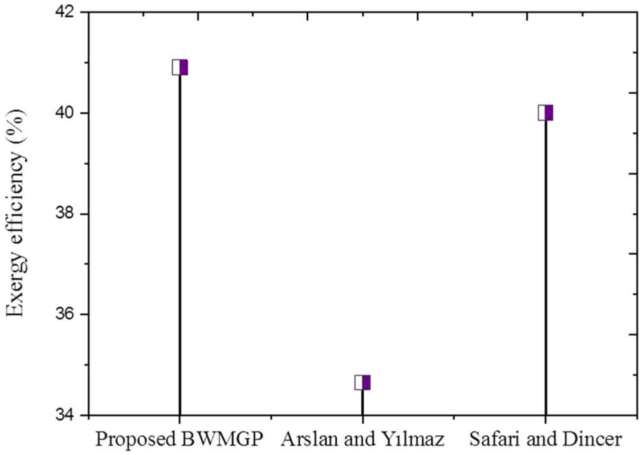


Figure 2. *A comparison between the exergetic performance of the introduced system and Arslan and Yilmaz [7] and Safari and Dincer [70].*

4.2. Overall results

The BWMGP's performance was thoroughly evaluated through thermodynamic, exergoeconomic and environmental analyses. Utilizing the thermodynamic-conceptual simulation developed in software, detailed thermophysical data for all streams depicted in Figure 1 were determined. The project yields three valuable outputs: electricity, water and hydrogen fuel. Based on various calculations and simulations, the plant is capable of generating an estimated 17 920 kW of electric power, 3207.6 kg/h of hydrogen energy and 5.14×10^{-3} L/s of freshwater. The system's energy efficiency under these design conditions is computed to be 35.76%, with the exergetic efficiency and destroyed exergy noted at 40.49% and 144 834 kW, sequentially. Figure 2 illustrates a comparison between the exergetic performance of the introduced system and the two systems previously documented in literature.

Figure 3 illustrates the variations in thermodynamic efficiencies of the BWMGP as it undergoes the process of unit completion and integration. This analysis considers six distinct configurations: Mode (I) involves coupling the Brayton power generation unit with the biomass's digestion. Mode (II) introduces the integration of the AWHU with the previously mentioned systems. Mode (III) incorporates processes for syngas and hydrogen generation. In Mode (IV), the system is further enhanced by integrating the RC. Mode (V) includes the integration of ORC units, and finally, Mode (VI) embodies the complete multigeneration process. The data demonstrate that system integration markedly enhances thermodynamic performance. Specifically, the energy and exergy efficiencies in Mode (VI), in comparison to Mode

Table 2. *Model verification: (A) Brayton cycle [68] and (B) gasification unit [69].*

A: Brayton cycle

Stream	Temperature		Mass flow rate		Pressure (bar)	
1	298.15 K	298.15 K	17 200 kg/h	17 200 kg/h	0.101 MPa	0.101 MPa
3	329.85 K	329.45 K	17 200 kg/h	17 200 kg/h	1.02 MPa	1.018 MPa
7	976.85 K	976.85 K	17 712 kg/h	17 820 kg/h	0.923 MPa	0.923 MPa
9	546.85 K	343.95 K	17 712 kg/h	17 820 kg/h	0.112 MPa	0.112 MPa
B: Gasification unit						
Constituent, vol. %			**H_2**	**CO**	**CO_2**	**CH_4**
Simulation			43.5%	33.2%	14.5%	9.1%
Literature			43.6%	33.3%	14.2%	8.9%

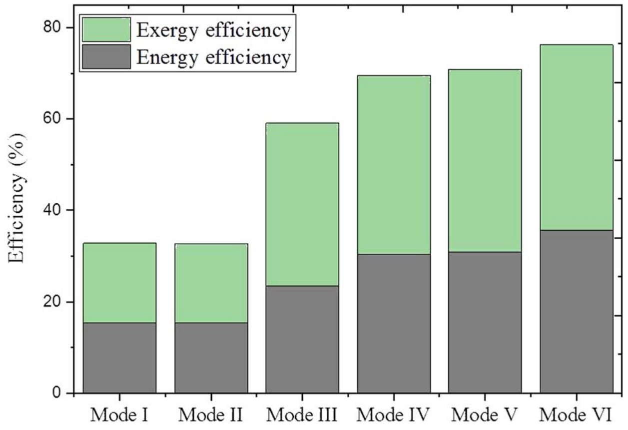


Figure 3. *The variations in thermodynamic efficiencies of the BWMGP as it undergoes the process of unit completion and integration.*

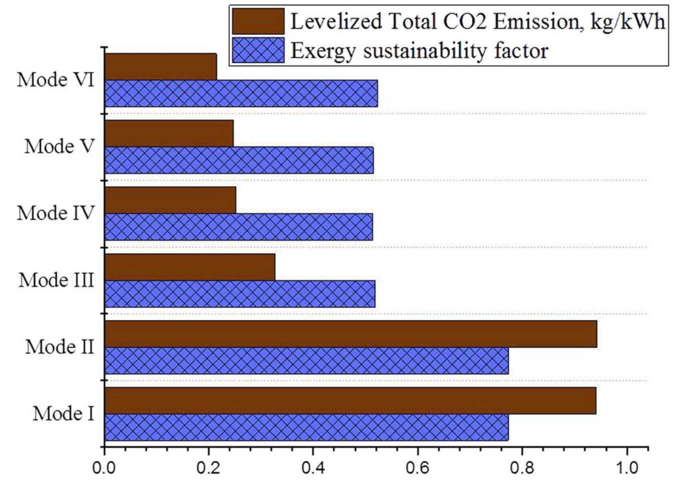


Figure 4. *The depiction of the exergy sustainability factor and levelized total emitted carbon for the BWMGP across various stages of completion and unit integration.*

(I), show substantial improvements of ∼130.18% and 131.77%, respectively. While it is evident that increased electricity production substantially boosts the system's energy efficiency, a noteworthy observation is the 15.25% increase in energy efficiency when transitioning from Mode (V) to Mode (VI), attributable to the additional heating capacity produced during Mode (VI).

The alteration in the destroyed exergy accounts for this observation (triggered by the incorporation of new components into the plant). Mode (III) exhibits the minimum exergy performance coefficient, attributing this to the gasifier addition, which escalates exergy destruction throughout the energy conversion process. Conversely, the depiction of the exergy sustainability factor and levelized total emitted carbon for the BWMGP across various stages of completion and unit integration is presented in Figure 4. The computed exergy sustainability factor for the proposed BWMGP stands at 52.28%. Notably, this factor demonstrates a linear decrease up to Mode (IV), but an increment of roughly 1.72% is observed in Mode (VI) compared with Mode (IV), indicating an enhancement in the system's environmental performance through integration. In a comparative view, the exergy sustainability factor and levelized total emitted carbon for the BWMGP in Mode (VI), in relation to a system coupled with a BC (Mode (I)), exhibit reductions (improvements) of ∼31.97% and 76.43%, respectively.

By pinpointing and optimizing the thermodynamic performance of such components, the overall efficacy of the energy conversion process can be elevated. The influence of each BWMGP's unit on the destroyed exergy is graphically represented in Figure 5. It is evident that the digestion and gasification (Dg and Ga) of biomass contribute predominantly to the BWMGP's exergy destruction, accounting for around 50% of the total destroyed exergy. These cycles involve three main components: a heat exchanger, a digester and a gasifier, with the gasifier alone responsible for ∼39% of the total destroyed exergy. Furthermore, the solar farm, despite being a vast energy reservoir, contributes over 25.8% of the total destroyed exergy due to the limited efficiency of the collectors in converting solar energy to heat. While these renewable energy-based units have high destroyed exergy values, their deployment substantially curtails environmental repercussions.

Financial projections indicate that the total capital cost for the proposed BWMGP is ∼2165.4 × 10^3 $ per year. Figure 6 delineates the financial contributions of each BWMGP's unit, highlighting that the solar farm, along with RC and ORC units, bear the brunt of the initial investment, cumulatively surpassing 72.8%

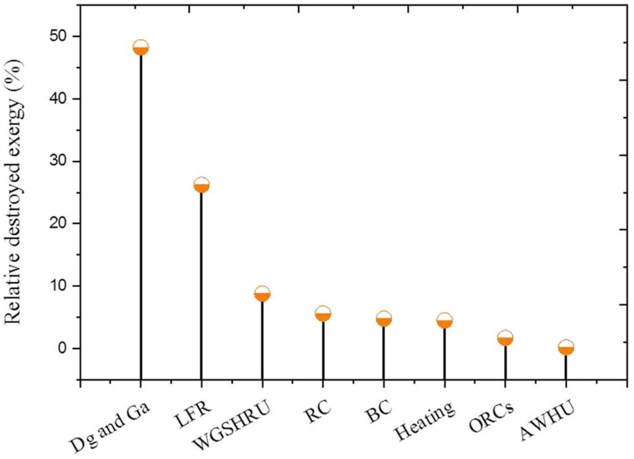


Figure 5. *The influence of each BWMGP's unit on the destroyed exergy.*

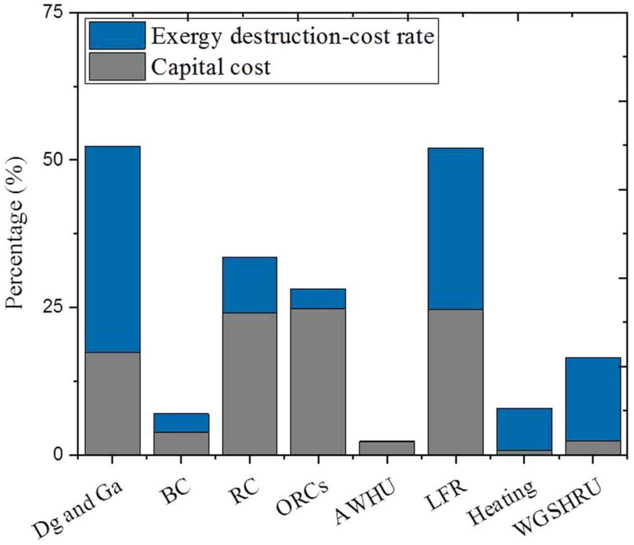


Figure 6. *The financial contributions of each BWMGP's unit.*

of the project's total initial outlay. The substantial investment in Rankine cycle and ORC units is principally due to the high turbines capitals. Balancing these financial aspects is crucial, particularly as nascent technologies typically demand higher investment. Consequently, the LFR and biomass-driven cycle incur relatively steep capital costs. However, a growing inclination toward renewable energy and technological advancements may diminish these costs over time.

The fuel Dg and Ga processes, along with the LFR, constitute ∼63% of the project's total exergy destruction cost rates. The exergoeconomic assessment further reveals that the condenser embedded in the second ORC system and the integrated heat exchanger in the cooling system possess high f_k values than other components. This underscores that capital investments in these components are substantial relative to their exergy destruction cost rates. Economically, opting for components with lower costs can enhance the project's financial performance. The calculated total products unit cost of the proposed plant stands at 0.05219 $ per kWh, a pivotal metric in the exergoeconomic/cost assessment of the plant. A comparison of this value with those documented in literature for analogous projects is presented in Figure 7, affirming the proposed project's superior cost advantage in producing divers products relative to many similar endeavors documented in scholarly publications. Additionally, the unit cost of hydrogen production in the proposed plant was characterized at 0.05029 $ per kWh, a critical indicator in appraising hydrogen production methodologies (see Table 3).

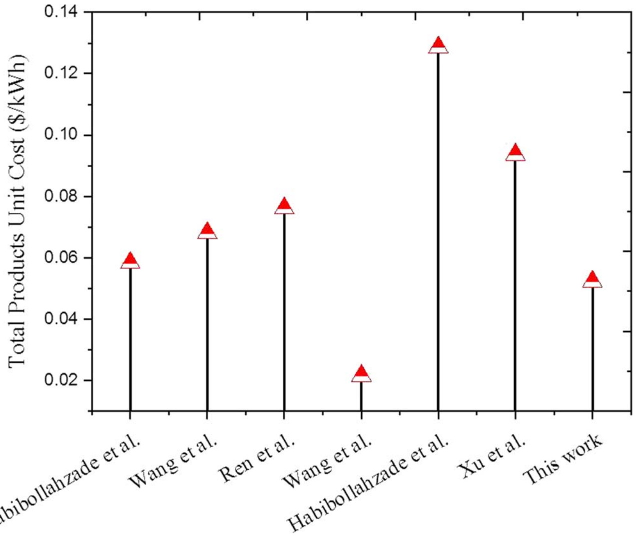


Figure 7. *A comparison of the total products unit cost value with those documented in literature for analogous projects: Habibollahzade et al. [71], Wang et al. [72], Ren et al. [73], Wang et al. [74], Habibollahzade et al. [75], and Xu et al. [76].*

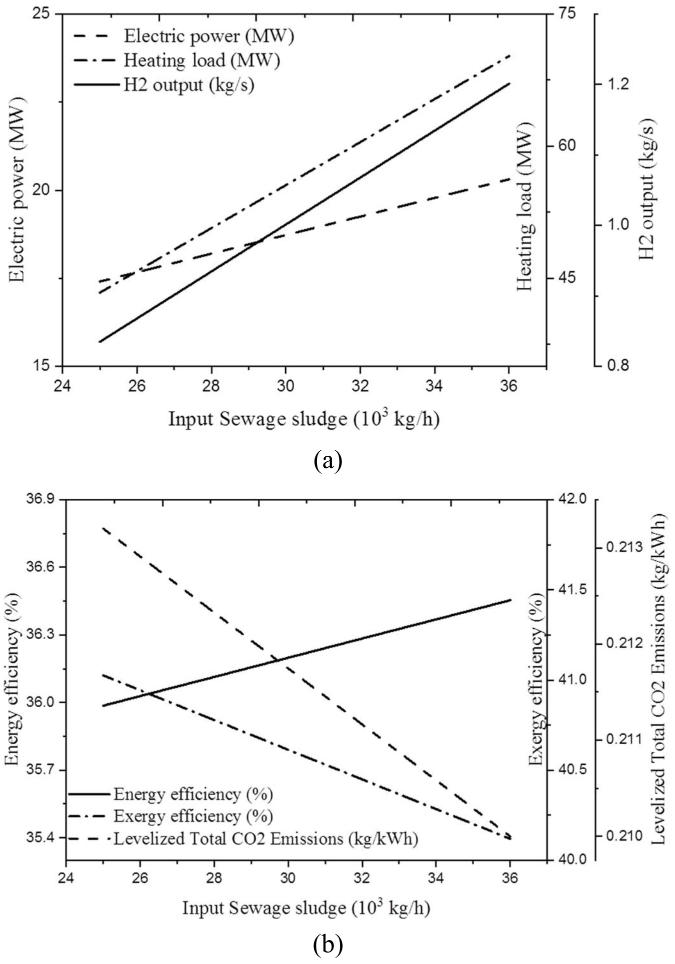
Besides its commendable thermodynamic and cost-efficiency, a novel energy project such as the presented BWMGP must also exhibit a capacity to diminish environmental impacts. Pertinent to this, the environmental analysis conducted reveals that the LTE-CO_2 value for the BWMGP stands at ∼0.2145 kg per kWh. This metric has undergone a comparative analysis with similar studies to gauge the environmental efficacy of the BWMGP. Therefore, reducing the carbon footprint (especially in urban societies) is of great importance [80, 81].

4.3. Parametric study results

The performance of the BWMGP is susceptible to variations in several independent parameters, including the input sewage sludge, inlet air temperature and relative humidity. The current study delves into how alterations in these parameters influence the multigeneration system's performance. Notably, the input biomass rate can significantly impact both the products outputs and the system's thermodynamic behavior. Figure 8 illustrates the repercussions of varying the input biomass rate on the BWMGP's functionality. An uptick in this flow rate bolsters the capture of biogas and syngas, thereby enhancing the outputs of electricity

Table 3. *A comparison of the hydrogen unit cost with those documented in literature for analogous projects*

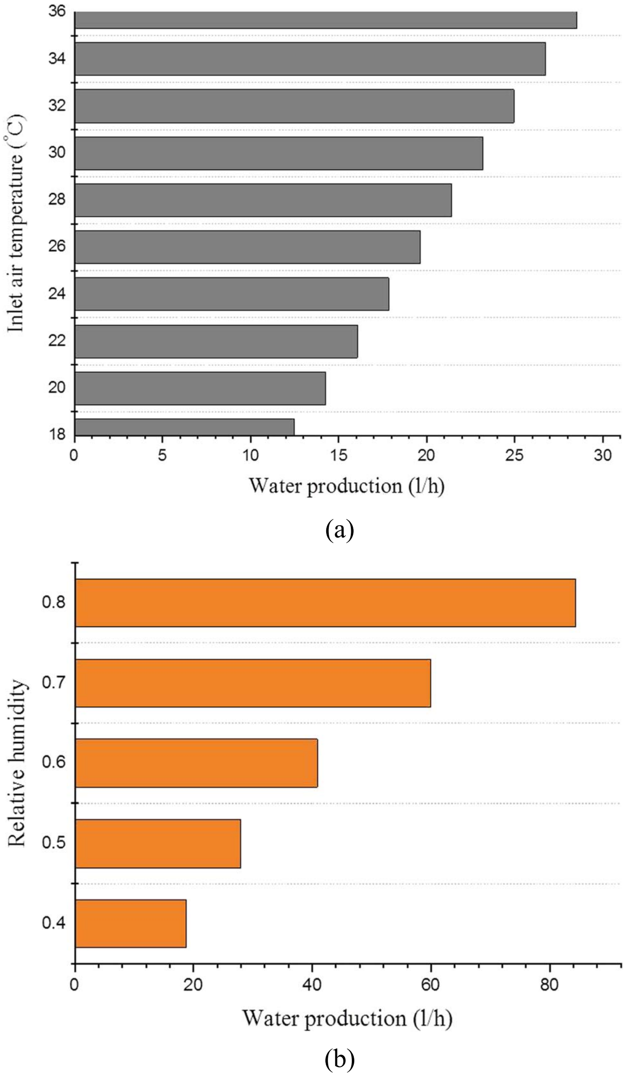
Ref.	Plant type	Input energy	Hydrogen unit cost ($/kWh)
This work	Multigeneration plant	Bio-waste and Solar	0.0498
[74]	Hybrid system	Biomass and Geothermal	0.2460
[77]	Integrated energy system	Flue gas	2.43
[78]	Multigeneration system	Biomass and Solar	0.1618
[79]	Polygeneration system	Ground source and Biomass	0.0734



(a)

(b)

Figure 8. *The repercussions of varying the input biomass rate on the BWMGP's functionality.*



(a)

(b)

Figure 9. *How the freshwater output of the BWMGP fluctuates with changes in the relative humidity and temperature of the inlet air (the AWHU).*

production units, WGSHRU and the heating generation unit due to an increase in received enthalpy.

In the examined range, as depicted in Figure 8b, an approximate 1.28% enhancement in energy efficiency was observed. Conversely, a surge in the sewage sludge flow rate instigates a decline in exergy efficiency. This phenomenon occurs because the rate of increase in the input exergy outpaces that of the output ones, resulting in diminished exergetic efficiency. Specifically, an escalation in the input biomass from 25×10^3 to 25×10^3 kg/h led to a decrease in exergy efficiency by roughly 2.3%. However, channeling more biomass to the plant is shown to bolster environmental impacts by lowering the LTE-CO_2. The improvement is attributed to the augmented availability of biomass fuel within the cycle, which escalates the flowed energy rate to bottoming units and concurrently curtails gas emissions into the atmosphere.

Furthermore, Figure 9 examines how the freshwater output of the BWMGP fluctuates with changes in the relative humidity and temperature of the inlet air (the AWHU). An increase in both parameters is shown to elevate the water production rate. As the temperature of the inlet air rises, so does the H_2O dew point, thereby enhancing the freshwater output. Moreover, augmenting the relative humidity (while maintaining a fixed temperature of inlet air) increases the H_2O density and, in turn, elevates the moist air dew point, culminating in an improved water production rate. Specifically, increasing the relative humidity from 40% to 80% results in an approximate 4.5-fold increase in the freshwater output, signifying a substantial enhancement.

5. CONCLUSIONS

The present paper developed a new bio-waste-based multigeneration plant that incorporates a solar farm which was introduced under the generation of diverse products such as electric power, freshwater, heat and hydrogen gas. The proposed MGP harnessed syngas and biogas from gasification and anaerobic digestion units, sequentially. Moreover, the production of water and hydrogen energy involved the AWHU and water/gas shift reaction ones. Additionally, a significant portion of heating capacity and electricity was derived from a waste heat recovery system, contributing to environmental conservation by minimizing waste discharge. The generation of green hydrogen via a BWMGP-based water/gas shift reaction presents a promising avenue for reducing environmental harm. The performance of this energy system was extensively assessed from thermodynamic, financial and environmental perspectives. The proposed plant is capable of producing an estimated 17 920 kW of electric power, 3207.6 kg/h of hydrogen energy and 5.14×10^{-3} L/s of freshwater. Under these design conditions, the energy and exergy efficiencies of the system were determined to be 35.76% and 40.49%, respectively. Additionally, the exergy sustainability factor, the levelized total emitted carbon dioxide and the unit cost of total products were characterized to be 52.28%, 0.2145 kg per kWh and 0.05219 $ per kWh, respectively.

In a comparative view, the exergy sustainability factor and levelized total emitted carbon for the BWMGP, in relation to a system coupled with a BC, exhibit reductions (improvements) of ~31.97% and 76.43%, respectively. Economically, it may be more feasible to use different processes' waste heat for the gasification process. Yet, from an environmental perspective and considering the limitations of fossil fuels, sourcing thermal energy from renewable resources, particularly solar energy, is the preferable approach.

AUTHOR CONTRIBUTIONS

Nadir Demir (Formal analysis [Equal], Writing—original draft [Equal]), Amir Mohammad Shadjou (Formal analysis [Equal], Investigation [Equal], Resources [Equal]), Maha Abdulameer (Methodology [Equal], Validation [Equal], Writing—review & editing [Equal]), Najah Almasoudie (Methodology [Equal], Writing—original draft [Equal]), Nerain Mohammed (Data curation [Equal], Resources [Equal], Writing—review & editing [Equal]), and Hadi Fooladi (Investigation [Equal], Project administration [Equal], Validation [Equal], Writing—review & editing [Equal])

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