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Thermo-eco-environmental Investigation of a Newly Developed Solar/wind Powered Multi-Generation Plant with Hydrogen and Ammonia Production Options

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A B S T R A C T

The current study introduces a ground-breaking multi-generation plant utilizing solar and wind energy. This study proposes a hybrid system that combines wind and a steam Rankine cycle for power generation. This integrated system aims to address cooling needs through a dual-effect cooling system and heating requirements through an steam Rankine cycle heat exchanger. Additionally, the system intends to produce hydrogen through a proton exchange membrane electrolyzer and ammonia via a reactor. This comprehensive approach investigates the potential for a more versatile and efficient plant design. This innovative system goes beyond electricity generation, offering a comprehensive solution for power (44.8 MW), heating (20.64 MW), cooling (123.9 MW), hydrogen (263.1 kg/h), and ammonia (106.48 kg/h) production. A thermo-economic-environmental analysis reveals promising performance with high energetic (83.65%) and exergetic (17.97%) efficiencies, an exergo-environmental impact factor (0.91) as well as a total product cost rate of $1.44/s. The parabolic trough solar collector optimization is crucial as it contributes to the majority (57%) of exergy destruction. Amongst investigated parameters, an ambient temperature of 35°C yields the best exergo-environmental performance.

1. Introduction

The ever-growing global energy demand necessitates a paradigm shift towards sustainable solutions. Fossil fuel dependence, with its detrimental effects on the environment, necessitates the exploration of clean and efficient alternatives [1].

Multi-generation plants (MGPs) powered by renewable sources like solar and wind offer a promising approach in this regard. Integrating these re-

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newable sources into MGPs presents significant advancements [2]. Firstly, it drastically reduces reliance on fossil fuels, leading to a decline in greenhouse gas emissions and air pollution. Secondly, renewable energy sources offer geographical dispersion and are not susceptible to price fluctuations like traditional fuels, fostering energy independence and mitigating the risks associated with geopolitical instability. Furthermore, MGPs can combine renewable energy sources with conventional methods, creating a more efficient system by utilizing waste heat from one process to power another, thus reducing overall energy consumption [3], 4]. Technological advancements in energy storage solutions like batteries are enabling MGPs to effectively manage the intermittency of solar and wind power, ensuring a more consistent and reliable energy supply. Finally, with the declining cost of renewable energy technologies, MGPs are becoming increasingly cost-competitive. Government incentives and carbon emission trading schemes further promote the economic viability of integrating renewable energy sources. Integrating hydrogen production units directly with renewable energy sources presents a promising solution. This approach not only fosters the environment-friendly generation of hydrogen but also significantly enhances the efficiency of MGPs. By utilizing renewable energy sources, these combined systems can significantly reduce their dependence on traditional fuels, leading to a cleaner energy footprint. Researchers are actively exploring the potential of hydrogen as a clean alternative. Bamisile et al. [5] investigated a MGP that utilizes a Rankine Cycle (RC) to generate electricity. This system also produced hot water, addressed cooling demands, and offered hydrogen as an additional output. Their analysis revealed an impressive overall energy efficiency of 71.6% and an exergy efficiency of 24.5%. Tukenmez et al. [6] designed a solar-powered a MGP. This system offers a comprehensive solution, generating electricity, providing cooling through an ejector subsystem, and producing hydrogen using a PEM electrolyzer (PEME). A thermodynamic assessment revealed promising results, with the plant achieving energy and exergy efficiencies of 59.3% and 56.5%, sequentially. Yilmaz et al. [7] investigated a MGP incorporating a solar section that utilizes a parabolic trough collector (PTC) technology. This versatile system caters to various needs, generating electricity, providing cooling and heating, producing potable water and hot water, and even offering hydrogen as an additional output. Their thermodynamic analysis yielded promising results, estimating the plant's thermal and exergy efficiencies to be 58.4% and 54.1%, respectively. Siddiqui et al. [8] proposed a MGP powered by solar energy. This system offers a dual functionality: generating electricity and producing hydrogen. An exergy analysis revealed an efficiency of 29.7%, while the total cost of operating the plant is estimated at approximately $63,345 per hour. Saleem et al. [9] devised and modeled a hydrogen production system powered entirely by solar energy. This design directly harnesses captured sunlight to fuel an electrolyzer, which in turn generates hydrogen. Their evaluation revealed an energy efficiency of 11.8% for this plant. Furthermore, they carried out a comprehensive analysis to investigate how various critical factors influence the system's performance. Colakoglu et al. [10] investigated an incorporated plant that utilizes solar energy. This system acts as a versatile source, generating multiple valuable outputs including hydrogen, electricity, cooling, and even domestic hot water. Their analysis focused on the exergy cost, revealing a competitive rate of 0.0798 dollars per kilowatt-hour for the entire range of products offered by the MGP. Researchers [11] investigated an alternative energy storage solution using ammonia fuel cells to address limitations like high combustibility, low storage efficiency, and costly infrastructure associated with conventional hydrogen fuel cells. Their analysis, applied within the context of smart grids and incorporating solar and wind power, demonstrated that this ammonia-based system effectively counteracts the inherent fluctuations observed in renewable energy sources. Yilmaz and Ozturk [12] presented a novel combined system capable of producing both ammonia and hydrogen. This innovative design underwent rigorous thermodynamic analysis, revealing an energy efficiency of approximately 61% and an exergy efficiency of around 57%. Furthermore, they conducted a parametric analysis to meticulously assess how individual parameters influence the system's overall performance. To ensure feasibility for large-scale ammonia production, a comprehensive exergy analysis was performed on the entire system. This analysis involved calculating the exergy efficiency not only for the entire system but also for each individual component.

Based on the reviewed literature, a new design has been proposed that combines a steam-powered cycle (SRC) with a dual-effect cooling system (DECS) and components for hydrogen production and ammonia conversion. This system is powered by a combination of solar and wind energy. Existing research has solely concentrated on economic and operational aspects, neglecting the environmental impact. This study aims to address this gap by performing a comprehensive evaluation of this recently introduced system, including an analysis of various parameters. In other words, this research seeks to broaden the understanding of this system by incorporating environmental considerations alongside economic and operational assessments. This study seeks to address crucial knowledge gaps by:

- To explore a novel MGP that utilizes a hybrid approach combining wind and steam Rankine cycle (SRC) for power generation. Additionally, the system aims to address cooling needs through a dual-effect cooling system (DECS) and heating requirements through an SRC heat exchanger. Furthermore, the MGP intends to produce hydrogen through a PEME and ammonia.
- To undergo a comprehensive assessment encompassing technical feasibility, environmental impact, economic viability, and sustainability.
- To identify the key factors influencing the system's performance across technical, economic, and environmental aspects.

The diagram in Figure 1 depicts the layout of the MGP, which utilizes renewable energy sources such as solar and wind power. It comprises various components like the SRC, DECS, wind turbine, PTC unit, PEME, and ammonia reactor. The PTC unit supplies energy to the HRVG, while the wind turbine serves as an additional power source. In the SRC, superheated steam is used to produce electricity and hydrogen. The working fluid is heated as it passes through the heat exchanger unit. In the DECS, water releases absorbed lithium bromide, with the resulting dense steam cooling in the DECS condenser. The DECS evaporator generates a cooling effect with cooled water. The PEME electrolyzes water using plant electricity to separate it into hydrogen and oxygen. In the final stage of the process, the ammonia reactor catalyzes the synthesis of ammonia by combining introduced nitrogen with the hydrogen generated within the system. This intricate cycle showcases the MGP's capacity to seamlessly integrate renewable energy sources and cutting-edge technologies to drive sustainable energy production and chemical synthesis.

2. Layout of the proposed plant

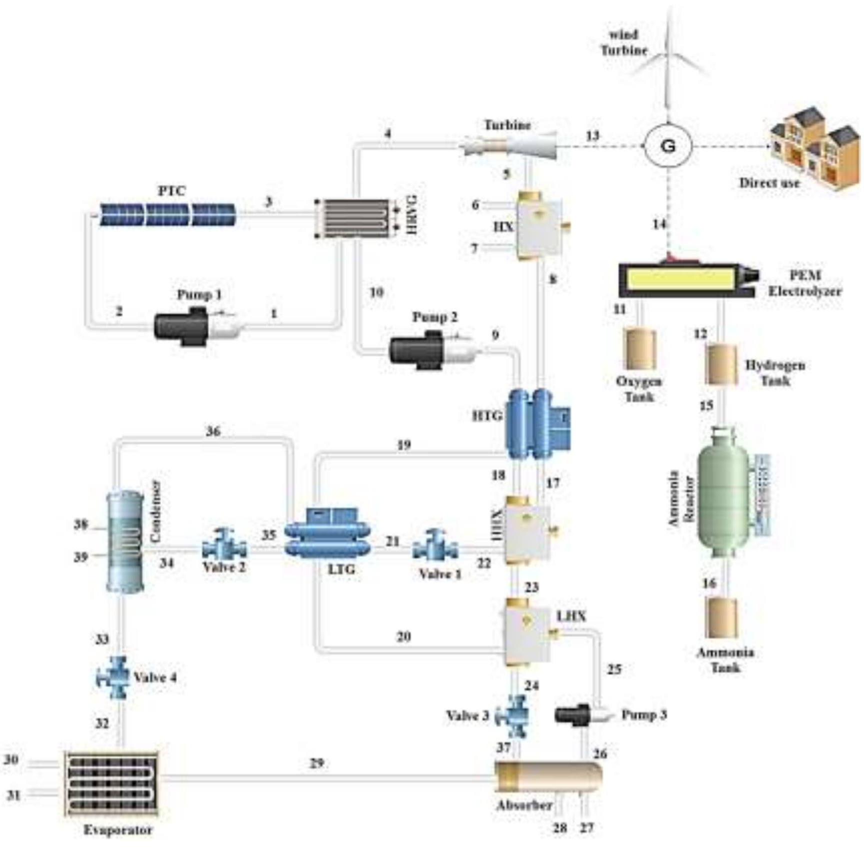

Figure 1. The solar/wind powered MGP layout

3. Methods of the modeling

In this particular section, it will be proceeding to illustrate the representation of mathematical modeling and its associated relations. In order to construct a precise model for the assessment of thermo-economic-environmental aspects, the utilization of EES software [13] has been deemed suitable, alongside the formulation of several plausible assumption [14], 15], 16] [17]:

- The surrounding environment is considered to be at a constant temperature of 25°C and a pressure of 101 kPa.
- All processes within the MGP are assumed to operate at a constant rate.
- Potential and kinetic energies, as well as exergies, are considered negligible during transformations within the system.
- An isentropic efficiency of 85% for turbine and 70% for pumps are assumed.
- The wind speed of 5 m/s, rotor diameter of 25 m, mechanical efficiency of 0.98, and power coefficient of 0.55 are considered.

3.1. Thermodynamic modeling

To energetically and exergetically model the given MGP, one can utilize the following equations to represent the principles of energy and mass conservation [16], 18]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\sum \dot{Q} + \sum \dot{m}_{input} h_{input} = \sum \dot{m}_{output} h_{output} + \sum \dot{W} \quad (2)$$

Where h, $\dot{m}$, $\dot{W}$, and $\dot{Q}$ represent enthalpy, mass flow rate, work rate, and the heat rate. The specific exergy of the substance, incorporating both physical and chemical components, and the destructed exergy rate are defined as follows [14], 19]:

$$ex = h - h_0 - T_0(s - s_0) + \sum x_k ex_{ch}^k + RT_0 \sum x_k \ln x_k \quad (3)$$

$$\dot{E}x_D = \sum \dot{Q}(1 - \frac{T_0}{T}) - \sum \dot{W} + \sum_i E\dot{x}_{inlet} - \sum_e E\dot{x}_{outlet} \quad (4)$$

Here 0, x_k and ex_{ch}^k signify the reference state, fraction of mass, and standard chemical exergy for each equipment in the compound which can be accessed in [20]. Also, the exergy of solar radiation and wind turbine are calculated as follows, in this work:

$$E\dot{x}_{solar} = \left[1 + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right)\right]\dot{Q} \quad (5)$$

$$E\dot{x}_{wind} = 0.5 A_w \rho_{air} V^3 \quad (6)$$

The Sun temperature, denoted as T_{sun}, is 5770 K [19]. In addition, the sustainability index (SI) is another associated factor that correlates with exergy efficiency. A comprehensive account of the energy balance and exergy destruction relations for all plant elements are provided in Table 1.

Table 1. The thermodynamic balances equations

Equipment	Energetically balance	Destructed exergy rate balance
Ammonia reactor	$\dot{Q}_{reac} = \dot{m}_{16}(h_{16} - h_{12})$	$ex_{14} - ex_{16} - \dot{m}_{16} LHV_{NH3}$
DECS	$\dot{E}_{DECS} = \dot{m}_{31}(h_{31} - h_{30})$	$E\dot{x}_8 - E\dot{x}_9 + \dot{W}_{pump2} - (E\dot{x}_{30} - E\dot{x}_{31})$
Heat exchanger	$\dot{E}_{heating} = \dot{m}_5(h_5 - h_8)$	$(E\dot{x}_5 - E\dot{x}_8) - (E\dot{x}_7 - E\dot{x}_6)$
HRVG	$\dot{m}_1(h_3 - h_1) = \dot{m}_4(h_4 - h_{10})$	$(E\dot{x}_3 - E\dot{x}_1) - (E\dot{x}_4 - E\dot{x}_{10})$
Direct use power	$\dot{W}_{net} = \dot{W}_{turbine}\eta_{EG} - (\dot{W}_{pump3} + \dot{W}_{pump2} + \dot{W}_{pump1} + e_{14}) + \dot{W}_{wind}$	
PEME	$\dot{E}_{PEME} = \dot{m}_{12} HHV_{hydrogen}$	$ex_{14} - (E\dot{x}_{12} + E\dot{x}_{11})$
PTC	$\dot{E}_{solar} = (T_3 - T_2) C_p \dot{m}_2$	$E\dot{x}_{solar} + E\dot{x}_2 - E\dot{x}_3$
Pump2	$\dot{W}_{pump2} = \dot{m}_9 v_9 (p_{10} - p_9) / \eta_{is,pump2}$	$\dot{W}_{pump2} + E\dot{x}_9 - E\dot{x}_{10}$
Turbine	$\dot{W}_{turbine} = \dot{m}_4(h_4 - h_5)$	$E\dot{x}_4 - E\dot{x}_5 - \dot{W}_{turbine}$
	$\eta_{is,turbine} = \frac{\dot{W}_{turbine}}{\dot{W}_{is,turbine}}$	

Wind turbine	$\dot{E}_{wind}=0.5\eta_w A_w C_p \rho_{air} V^3$	$E\dot{x}_{wind}-\dot{E}_{wind}$

The detailed equations for PTC and PEME modeling can be found in [21]. Finally, the energetic and exergetic efficiencies of the MGP are written as:

$$\eta_{MGP}=\frac{\dot{W}_{net}+\dot{E}_{heating}+\dot{Q}_{reac}+\dot{E}_{PEME}+\dot{E}_{DECS}}{\dot{E}_{solar}+\dot{E}_{wind}} \quad (7)$$

$$\varepsilon_{MGP}=\frac{\dot{W}_{net}+\dot{E}x_{30}-\dot{E}x_{31}+E\dot{x}_{7}-E\dot{x}_{6}+\dot{E}x_{12}+E\dot{x}_{16}}{\dot{E}x_{wind}+\dot{E}x_{solar}} \quad (8)$$

The SI is a metric that is commonly utilized in the realm of sustainability [22]:

$$SI=1-1/\varepsilon_{MGP} \quad (9)$$

3.2. Thermoeconomic modeling

This evaluation is based on the Specific Exergy Costing (SPECO) method [23], where the plant takes into account all inputs and outputs in a systematic manner, documenting all exergy additions and eliminations. Additionally, all costs are considered using the unit costs of the streams. Thus, a linking between the products and fuels of the plant and the corresponding costing equations is established. An overall cost flow rate balance can be written as follows [19]:

$$\sum^{N}(\dot{C}_{outlet})_k+\dot{C}_{W,k}=\dot{C}_{Q,k}+\dot{Z}_k+\sum^{N}(\dot{C}_{inlet})_k \quad (10)$$

$$\dot{Z}_k=z_k\times\varphi\times(ir(ir+1)^{ny}/((1+ir)^{ny}-1))/N_k \quad (11)$$

Here, the symbol $\dot{C}$ denotes the cost rate linked with exergy flow. The maintenance factor (φ) is assumed to have a value of 1.06, and the symbol N represents the number of working hours per year for the plant, which is set at 7440 hours. The symbols ir and ny correspond to the rate of interest (assumed to be 10%) and the plant's lifetime (assumed to be 20 years), sequentially. The presented MGP elements are accompanied by the cost balance and auxiliary equations, along with the costs of capital investment, which can be found in Table 2.
Finally, the total product cost rate is written as:

$$\dot{C}_{p,MGP}=\dot{C}_{f,MGP}+\dot{Z}_{MGP} \quad (12)$$

3.3 Exergo-environmental modeling

Understanding the environmental impact of the destroyed exergy requires a special analysis method. This method uses an index that combines two factors: index of exergo-environmental impact (θ_{ei}) and exergo-environmental impact factor (f_{ei}) that shows how much exergy is destroyed against the inlet exergy. Thus, θ_{ei} is written as [24]:

$$\theta_{ei}=100\frac{f_{ei}}{\varepsilon_{MGP}} \quad (13)$$

The steps involved in evaluating the offered MGP from a technological, economic, and environmental perspective are shown in Figure 2.

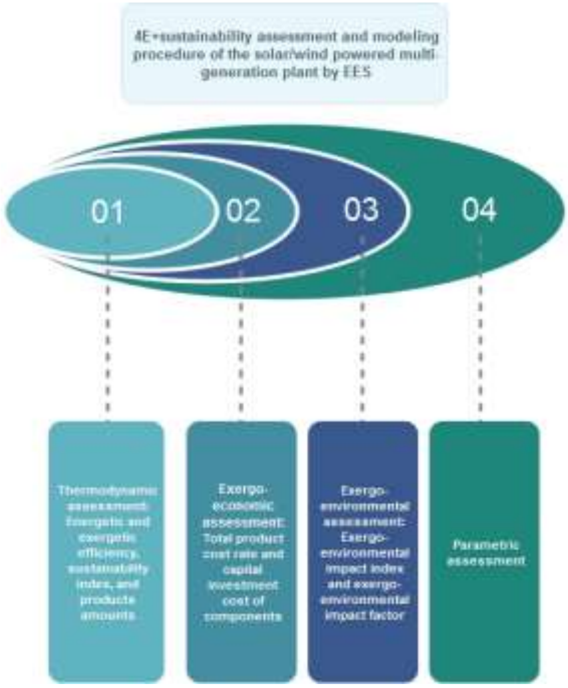

Figure 2. The steps involved in evaluating the offered MGP

4. Results and discussion

This section presents the results of the investigation and analyzes their significance. To clearly show these findings, detailed graphs and tables are included. Additionally, a parametric analysis is conducted to analyze how key factors can influence the performance of the MGP. Table 3 summarizes the most important findings from the analyses.

Table 2. Cost balances of the MGP equipment [24], 25]

Equipment	Cost balance	Supplementary equation	Cost functions
DECS	$\dot{C}_8 - \dot{C}_{Evaporator} = \dot{C}_9 - \dot{Z}_{DECS}$	$c_8 = c_9$	$z_{DECS} = 1258 \times \dot{E}_{DECS}^{0.6}$
HRVG	$\dot{C}_3 - \dot{C}_1 + \dot{C}_{10} = \dot{C}_4 - \dot{Z}_{HRVG}$	$c_3 = c_1$	$z_{HRVG} = 120 \times (\frac{A_{HRVG}}{0.09})^{0.7}$
PEME	$\dot{C}_{11} = \dot{C}_{14} - \dot{C}_{12} - \dot{Z}_{PEME}$	$c_{11} = 0$	$z_{PEME} = 905 \times \dot{E}_{12}$
PTC	$\dot{C}_2 + \dot{C}_s + \dot{Z}_{PTC} = \dot{C}_3$	$\dot{C}_s = 0$	$z_{PTC} = 13920 \times A_{PTC}^{-0.17}$
Pump2	$\dot{C}_{\dot{W}_{pump2}} + \dot{C}_9 + \dot{Z}_{Pump2} = \dot{C}_{10}$	-	$z_{Pump2} = 705 \times (1 + \frac{0.2}{1-\eta_{pump2}}) \times \dot{W}_{Pump2}^{0.7}$
Turbine	$\dot{C}_4 - \dot{C}_{\dot{W}_{turbine}} = \dot{C}_5 - \dot{Z}_{turbine}$	$c_4 = c_5$	$z_{turbine} = ((\frac{0.051}{(1-\eta_{is,turbine})^3}) + 1) \times 3880 \times \dot{W}_{turbine}^{0.7} \times (1 + (5 \times (\exp\left(\frac{T_4 - 868}{10.51}\right))))$
Ammonia reactor	$\dot{C}_{Q_{reac}} + \dot{C}_{12} + \dot{Z}_{reac} = \dot{C}_{16}$	-	$z_{reac} = 283 \times \dot{Q}_{reac}$
Wind turbine	$\dot{C}_{wind} = \dot{Z}_{wind} + \dot{C}_{wt}$	$c_{wt} = 0$	$z_{wind} = 5000 \times \dot{E}_{wind}$
Heat exchanger	$\dot{C}_5 + \dot{C}_6 + \dot{Z}_{HX} = \dot{C}_8 + \dot{C}_7$	$c_5 = c_8$, $c_6 = 0$	$z_{HX} = 131 * (\frac{A_{HX}}{0.09})^{0.7}$

Table 3. The most important findings of solar/wind powered MGP

Parameter	Amount
Ammonia rate (kg/h)	106.48
Cooling effect (MW)	123.9
Energetical efficiency (%)	83.65
Exergetical efficiency (%)	17.97
Exergo-environmental impact factor (-)	0.91
Heating effect (MW)	20.64
Hydrogen rate (kg/h)	263.1
Index of exergo-environmental impact (-)	5.07
Direct use power (MW)	44.8
Sustainability index (-)	1.22
Total cost rate of product ($/s)	1.44

Figure 3 illustrates how much exergy is destroyed in various components of the proposed MGP. The key finding of this figure is that PTC, wind turbine, and DECS units contribute most to exergy destruction in the MGP. This is because of temperature differences between the working fluid and the receiver in the

PTC, and between the lithium bromide-water solution and the vapor in the DECS.

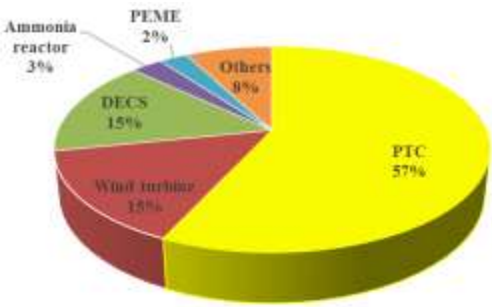

Figure 3. The share of destroyed exergy for the MGP units

According to Figure 4, the analysis of electricity generation and consumption in the facility reveals that the SRC plus wind turbines provide a total of 61 MW of electricity. Out of this generated power, 16.2 MW is used by the PEME plus pumps, while the remaining 44.8 MW is directly consumed by the plant itself.

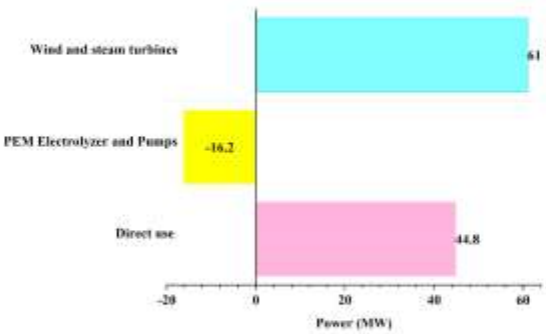

Figure 4. The analysis of electricity generation and consumption in the MGP

Figure 5 explores how changing the quality of the inlet to the High-Temperature Generator (HTG), represented by X8, affects the efficiency and cost of the MGP. When X8 increases from 0.55 to 0.75, the energy supplied to the Desorption Electro-Chemical System (DECS) increases, while the cooling load required decreases. However, the increase in energy consumption outweighs the decrease in cooling demand, resulting in a net improvement in overall energy efficiency of around 7%. On the other hand, the exergetic efficiency, which considers the quality of usable energy, decreases significantly because the exergy supplied to the heat exchanger decreases as X8 increases. This decrease in exergy is likely due to a larger temperature difference between the hot and cold streams in the heat exchanger. Additionally, a higher cooling load translates to greater DECS expenditure, which is a major factor influencing the overall product cost of the MGP.

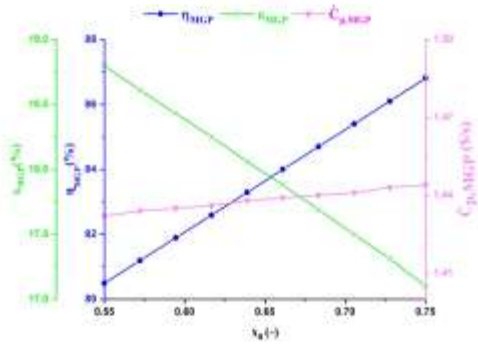

Figure 5. The power of input quality of the HTG on the cost and efficiencies of the MGP

Figure 6 shows how increasing the temperature difference of the HRVG loop affects the energy and exergy efficiencies, along with the total product cost of the MGP. The trend suggests that a higher temperature difference leads to improved system performance. This is because more working fluid can flow through the SRC as a result, generating more usable outputs from the system. This improvement in efficiency translates to a lower investment cost, ultimately reducing the overall product cost of the MGP.

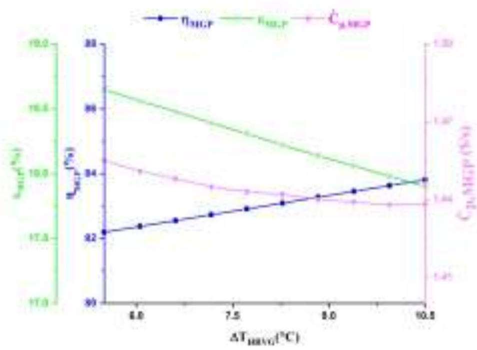

Figure 6. The power of HRVG temperature difference on the cost and efficiencies of the MGP

An increase in the PTC length, ranging from 46 meters to 53 meters, is investigated in Figure 7 to examine its influence on the MGP's operating criteria.

A longer PTC allows for greater capture of solar energy, translating directly into a rise in the plant's net power output. This enhanced solar energy utilization also leads to a greater temperature increase within the solar system. As a result, the plant generates additional electricity, consequently improving both its energy and exergy efficiencies. It's important to note that while the MGP's exergetic efficiency increases with a longer PTC, this comes at a cost. The total unit exergy cost rises significantly within the examined range. This cost increase is likely due to the additional investment required for a larger PTC, ultimately pushing up the system's overall product cost rate.

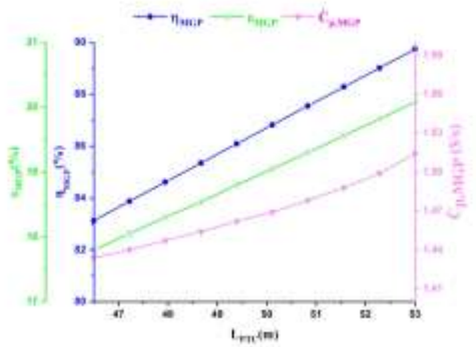

Figure 7. The power of length of the PTC on the cost and efficiencies of the MGP

Figure 8 explores the relationship between turbine inlet pressure (P4) and the exergo-environmental impact factor of the MGP at different reference temperatures. The results suggest that increasing P4 has a detrimental effect on the environment from an exergy perspective. This is because a higher P4 leads to a rise in the MGP's total exergy destruction rate. In simpler terms, the plant operates more environmentally friendly at higher reference temperatures. This is because lower overall exergy destruction is achieved at these temperatures.

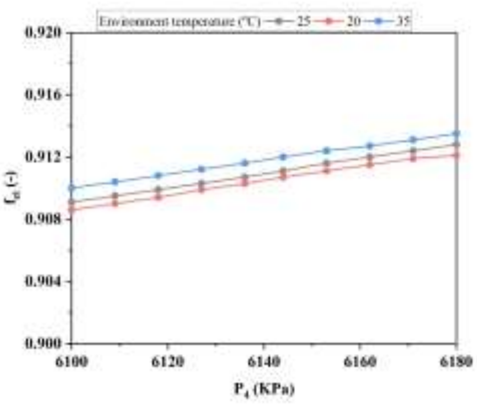

Figure 8. Power of Turbine inlet pressure on the exergo-environmental impact factor at different environment temperature

5. Conclusions

This study proposes a groundbreaking MGP that leverages solar and wind energy sources. This novel design goes beyond just electricity generation, offering a comprehensive solution for power, heating, cooling, hydrogen, and ammonia production. To rigorously evaluate the MGP's performance across all these aspects, we employed a thermo-economic-environmental analysis. The following section summarizes the key takeaways from this investigation.

- The analysis revealed promising results for the MGP's performance. The plant achieved an energetic efficiency of 83.65% and an exergetic efficiency of 17.97%. It also demonstrated its ability to generate 44.8 MW of direct power, alongside 20.64 MW for heating and 123.9 MW for cooling. Additionally, the MGP produced 106.48 kg/h of ammonia and 263.1 kg/h of hydrogen. Furthermore, the economic and environmental aspects were assessed, resulting in a total product cost rate of \$1.44/s and a favorable exergo-environmental impact factor of 0.91.
- The analysis of exergy destruction revealed that the PTC was the biggest culprit, accounting for a substantial 57% of the total.
- To understand how different factors, affect the MGP's performance, three key variables were investigated: HRVG temperature difference, PTC length, and HTG inlet quality. The analysis revealed that from an exergo-environmental perspective, the plant performs best at an ambient temperature of 35°C.

Nomenclature

A	Area, m^2
$\dot{C}$	Cost rate, \$/s
CRF	Capital Recovery Factor
DECS	Dual-Effect cooling system
EES	Engineering Equation Solver
$\dot{E}x$	Rate of exergy, MW
f_{ei}	The factor of exergo-environmental impact
h	Specific enthalpy, kJ/kg
HX	Heat exchanger
HHX	High-temperature heat exchanger

HTG	High-temperature generator
LHX	Low-temperature heat exchanger
LTG	Low-temperature generator
$\dot{m}$	Rate of mass flow, kg/s
P	Pressure, kPa
PEME	Proton Exchange Membrane Electrolyzer
s	Specific entropy, kJ/kg.K
SPECO	Specific exergy costing
T	Temperature, K
$\dot{W}$	Power rate, MW
X	Quality
z	Cost of capital investment, $
$\dot{Z}$	Rate of investment cost, $/s
Greek letters	
η	Energetic efficiency
ε	Exergetic efficiency
φ	Maintenance factor
θ_{ei}	Index of exergo-environmental impact
Subscripts	
0	Environment condition
D	Destruction
tot	Total

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