Energy, exergy, exergoeconomic, and exergoenvironmental study of an innovative solar-wind-biomass driven polygeneration system for power, heat and ammonia production

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Abstract:

Global warming has increased the use of renewable energy in energy systems. In this regard, the present work presents an innovative polygeneration system to produce power, ammonia, and process steam using solar, biomass, wind, and geothermal energies. By using a solar-syngas hybrid boiler, steam has been created in two high-pressure (HP) and low-pressure (LP) levels, and the HP steam is used for the gasification process. Syngas produced from biomass gasification process produces ammonia with the nitrogen obtained from an air separation unit by going through water gas shifting and carbon capture processes. Power consumption in the mentioned sections is produced by wind turbines. A Brayton cycle with ammonia and hydrogen hybrid fuel has been used to produce power and heat. The integration of supercritical CO_2 and organic Rankine cycles with the hot flue gas output from the Brayton cycle has reduced heat losses and increased power generation. The presented renewable system has been analysed from the point of view of energy, exergy, exergeoeconomic, and exergoenvironmental (4E) methods. The overall results indicate that the total energy and exergy efficiencies are 31.33% and 38.53%, respectively. Also, the cost rate and environmental impacts of the whole system are calculated as 3222.35 $/h and 53.16 Pts/h, respectively. Meanwhile, the levelized cost and environmental impacts of electricity are equal to 0.18 $/kWh and 0.003 Pts/kWh, and the presented system is capable of producing 297.86 ton/day of ammonia.

Keywords:

Ammonia synthesis; Solar and biomass; Wind energy; Geothermal; Polygeneration.

1. Introduction

In the field of energy, there are various crises that indicate the importance of using renewable resources as a sustainable solution for energy production. These crises include rising prices of fossil fuels, decreasing levels of oil production, increasing air pollution, and the effects of desertification and global warming. In addition to the existing crises in the field of energy, energy production is also facing environmental crises. The use of fossil fuels leads to an increase in greenhouse gases and climate change, which has serious effects on life globally. Also, the use of fossil fuels causes air pollution and an increase in respiratory-related diseases. Biofuel production has been considered as a sustainable solution for energy production due to its biological properties. Biofuel is obtained from renewable sources such as plants, agricultural waste, and other organic materials and reduces greenhouse gases and air pollution [1]. In 2020, more than 80% of the installed power capacity worldwide was supplied by renewable sources [2]. This percentage will likely increase due to the increasing growth of the renewable industry.

 https://doi.org/10.52202/069564-0063

One of the famous examples of biofuels is ammonia. Ammonia is one of the most widely used chemicals in the world. Ammonia synthesis from natural gas reforming [3], or ammonia production with syngas is one of its production methods [4]. Recently, the idea of creating an alternative fuel for fossil fuels has arisen, hydrogen can be converted into ammonia and then ammonia can be used as a fuel [5]. In addition, producing ammonia and replacing it with fossil fuels has advantages, including reducing air pollution and generating energy [6]. Furthermore, considering that hydrogen is not easily accessible and its storage is not necessarily easy, producing ammonia from hydrogen as an alternative approach has many advantages. In this regard, Aziz et al [7]. showed in their research that ammonia can be used in internal combustion engines, combustion for gas turbines, and direct ammonia fuel cells due to its high efficiency. Also, Lamb et al [8]. proposed hydrogen storage by ammonia production as a suitable way to transport and store it. Tinoco Caicedo et al [9]. conducted a study using biofuels in tri-generation systems to meet the energy demands of an instant coffee plant located in Guayaquil, Ecuador. The results show an increase in exergy efficiency from 51.9% to 84.5%

The use of renewable energies such as wind, solar, geothermal, and biomass is highly justifiable due to the countless benefits they have in the fields of energy, economy, health, and the environment [10]. Although each of the renewable energies individually creates many possibilities for us, the integration of these energies can significantly improve efficiency and reduce energy production costs [11]. Mousavi Rabati et al [12]. have proposed an integrated multi-generation system based on renewable energy sources such as solar and biomass for the production of power, heat, freshwater, and hydrogen. Their analysis results show that for Municipal Solid Waste (MSW) fuel, the overall energy and exergy efficiencies of the multi-generation system are 39% and 32.01%, respectively. The flexibility of renewable energy systems allows us to have the most efficient energy production systems in any condition. Borhanazad et al [13]. showed the potential of using wind, solar, and water energy well for two states in Malaysia to provide electricity. In these two states, due to the high potential of solar radiation, they can produce 3182 kW and 6317 kW through 18 and 22 sites, respectively. During their research in Europe and Latin America, Bersalli et al [14]. observed the positive impact of using renewable energy sources on reducing the economic costs of energy production. Khani et al [15]. demonstrated a multi-technology solar-based energy production system, which integrates gas and steam turbine cycles, organic Rankine cycle (ORC), and carbon dioxide capture, Humidification-dehumidification (HDH), showing that electricity production can be increased from 37.3% (in winter) to 59.41% (in summer) by integrating solar energy.

There are different solutions for integrating energy systems, for example, cogeneration and polygeneration systems can be used [16]. The Brayton cycle is one of the processes in cogeneration, in which electricity and heat are produced using a fuel such as ammonia. The goal of using renewable fuels is to reduce the environmental impact of using fossil fuels [17]. Also, the Supercritical CO_2 (S-CO_2) cycle is a power generation technology in which supercritical carbon dioxide is used as the working fluid in a closed-loop system. The supercritical carbon dioxide cycle offers several advantages over traditional steam-based cycles in energy systems, such as higher efficiency, lower footprint, lower capital costs, and lower greenhouse gas emissions [18]. The economic and environmental characteristics of a multi-generation system are very important. Multi-generation production systems can be used in various industries, such as freshwater production [16]. Diyoke and Ngwaka [19], integrated a gasifier, a syngas electric motor, connected to an absorption refrigeration system, and a wind turbine generator. They observed that the overall energy efficiency and exergy efficiency were 0.48 and 0.25, respectively, and major exergy destruction of about 95% for this system in this system, wastes are first collected and separated, and then sent to processes for energy production [20].

Despite extensive research in the field of renewable energy systems, the dependence of these systems on fossil fuels is still felt to create stability. Therefore, presenting a system that is entirely based on renewable energies requires further research. In this regard, the present work focuses on utilizing solar, biomass, and wind energies to produce ammonia as an alternative fuel for energy systems. The ammonia produced as a biofuel is then used in the Brayton cycle to generate sustainable power. The integration of S-CO_2 cycles and ORC in this system has increased power production and improved the efficiency of the studied system. Finally, by conducting energy, exergy, economic, and environmental analyses for the studied system, the feasibility of operating such a system has been examined in more detail. A series of innovations carried out in the present work are as follows:

- Ammonia production has been done using the integration of solar, wind, and biomass energies.
- The gas turbine cycle with a combined fuel of ammonia and hydrogen has been analyzed.
- The integration of S-CO_2 and ORC with the Brayton cycle based on ammonia has been investigated.
- Machine learning has been used to analyze and model parts in the processing unit.

2. System description

In this work, a polygeneration system based on solar, wind, geothermal, and biomass renewable energy is proposed to produce ammonia, power, and heat (process steam). This system has been analyzed for the city of Tehran in Iran. Tehran is located at 51° 6' to 51° 38' east longitude and 35° 34' to 35° 51' north latitude. The solar irradiance in Tehran is about 1800 to 2200 kilowatt-hours per square meter per year. The average wind speed in this city is around 4.5 meters per second [21], and the geothermal source in Tehran can provide heat up to 110 degrees Celsius for the energy systems. Also, the biomass used in the system is municipal solid waste (MSW), and its annual production in Tehran is around two million tons on average. The designed system consists of sections for ammonia synthesis, CO_2 capture, water gas shift (WGS), gasification process, ORC (R123), S-CO_2 cycle, and Brighton cycle. Their explanations are given below. Based on Figure (1), which illustrates the schematic of the designed system, it can be stated that after the water makeup, steam is produced at two pressure levels, LP and HP, from a hybrid solar-syngas boiler using syngas as fuel. The produced LP steam is used as a process steam, while the HP steam is fed into the gasification reactor for the production of synthesis gas using the air-steam gasification agent. The chemical reaction that occurs in the gasifier is as follows:

$$CH_{\alpha}O_{\beta}N_{z} + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4, \quad (1)$$

In the boiler, water is initially preheated by the heat of the syngas outlet from the gasifier and the heat resulting from its combustion in the boiler, and exits the system from the stream (4) and by solar energy, it loses its latent energy and enters the boiler and the LP steam leaves the stream (8). In the same way, another part enters and leaves the boiler with a higher pressure (HP) to enter the gasifier and produce syngas. The use of solar energy has been used as an aid to produce steam in the boiler. The second section of the syngas stream, which is the stream (21), enters the WGS stage to convert the CO in the syngas to CO_2. Its reaction is reported in relation (2):

$$CO + H_2O \leftrightarrow CO_2 + H_2, \quad (2)$$

The final synthetic gas, devoid of CO, is directed into a CO_2 capture process. Using an air separator unit (ASU), nitrogen is added to the exhaust gas from the CO_2 capture to produce ammonia with higher and more suitable efficiency, and gas rich in nitrogen and hydrogen enters the ammonia synthesis stage. In this section, the ammonia reaction takes place through two converters with a conversion efficiency of 25%, operating at a temperature and pressure of 350 ℃ and 30 bar, respectively [4, 22]. The ammonia reaction is as follows:

$$N_2 + 3H_2 \leftrightarrow 2NH_3, \quad (3)$$

The produced ammonia with a purity of 99% is removed from the separator, and a part of it is stored while the other part is used to maximize the use of the system designed for burning in the Brayton cycle, which is coupled with a PEM electrolyzer (PEMEC) to provide hydrogen for the combustion chamber. Hydrogen is added to ammonia to increase the fuel's calorific value. It is also noteworthy that the power required for the operation of the PEMEC and ASU in the CO_2 capture section is supplied by renewable wind energy through wind turbines. The wind turbine used is LTW77 and has a capacity of 1MW [23]. The required heat for the S-CO_2 cycle and ORC is supplied from the exhaust temperature of the gas turbine, which is high to reduce losses, recover heat, and generate power. The working fluid used in the Rankine cycle is R123, which utilizes geothermal energy to change the phase of the output water stream (55). Assumptions used in the proposed system:

- The system has been studied in a steady state, and kinetic and potential energies in all flows have been neglected.
- There is enough time to carry out the gasification reaction, so this equilibrium process is carried out
- Gasification pressure is considered constant.
- The production of tar and char in gasification has been disregarded.
- Heat losses in all heat exchangers have been disregarded.
- The temperature and working pressure of WGS reactors are 450 ℃ and 14.4 bar, respectively, and their fractional conversion is 88.2 [22].
- Ambient temperature and pressure are considered to be 25 ℃ and 1.01 bar, respectively.
- The collectors used are PTC and their model is ET100 [24].
- The temperature and pressure are assumed to be constant in the PEMEC, equal to 80 ℃ and 1 bar, respectively [25].
- The production of nitrogen oxides, sulfur, chlorides, etc. in the syngas products has been disregarded.

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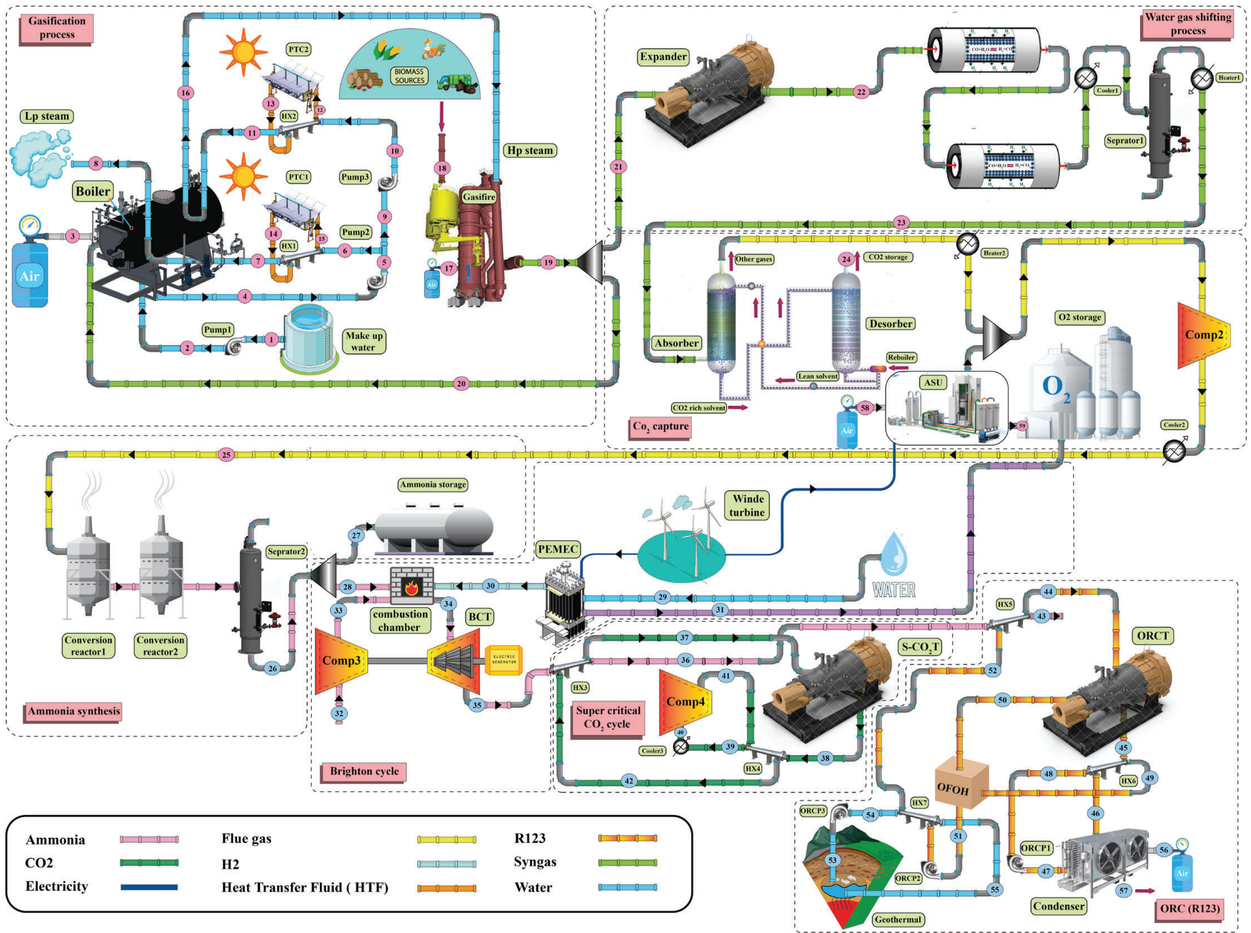

Figure. 1. Schematic of polygeneration system based on solar, wind, geothermal, and biomass renewable energy to produce ammonia, power, and heat

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3. Governing equations

To calculate the heat and power exchanged by an energy system in a steady state, the mass and energy balances can be calculated based on the first law of thermodynamics, and the equations are as follows [26]:

$$Q - W = -\sum_{i=1}^{n} m_{out}\left(h + \frac{V^2}{2} + gz\right)_{out} - \sum_{i=1}^{n} m_{in}\left(h + \frac{V^2}{2} + gz\right)_{in}, \tag{4}$$

$$\sum_{i=1}^{n} m_{out} = \sum_{i=1}^{n} m_{in}, \tag{5}$$

In equation (4), Q is the heat transfer rate, W is the power transfer rate, and m_{in} and m_{out} are the input and output mass flow rates. Also, each input and output flow has parameters g gravity, h specific enthalpy, v velocity, and z height. It should be noted that in flows where the potential and kinetic energy values are negligible, these terms are disregarded. However, for inflows such as the inflow and outflow of wind turbines where the kinetic energy is important, this term is included. By using the conventional principle of state and knowing two independent thermodynamic variables, it is possible to calculate other thermodynamic variables. Writing the energy and mass balance for all equipment is not enough because these equations consider the system in a closed state and only check the input and output flows to this system. If necessary, to investigate mass transfer, heat transfer, and other important parameters in equipment, additional equations must be involved for each piece of equipment. For example, in PTC, energy transfer is not the only issue and the required collector surface is also important, so it is necessary to use heat transfer equations to calculate it. Also, in a gasification reactor, it is necessary to balance the molar flow rates based on equilibrium constants to calculate the molar coefficients on the reactant side. For process systems such as ASU and ammonia production, writing the energy and mass balance and modeling these systems is very complicated. The equipment in these systems all have equations related to energy and mass balance, and each piece of equipment can also be divided into several sub-systems. As there are feedback currents in these systems, modeling them, like other components of the system, will be very time-consuming and complex. Therefore, machine learning or faster alternative methods are suggested for these systems. In the present work on the gasification system, ASU, and ammonia production, machine learning has been used, and the equations governing these systems have been extracted. The equations are extracted by simulating or modeling each of the mentioned systems in software. For ASU, it was simulated in Aspen Plus software according to the reference [27]. For ammonia production, it was simulated in Aspen Hysys software based on the reference [22]. For gasification, modeling was performed using MATLAB software based on the article by Sirinivas et al [28]. After that, the validation was done and the data bank was formed by repeated calculations to extract comprehensive relationships by Python software. For analyzing and investigating other equipment such as PEMEC, equations from the reference [25] have been utilized. For wind turbines, references [23, 29] were employed. For PTC, references [24, 30] were used, and for gasification, reference [28] was employed. In the current work, exergy analysis, exergoeconomic analysis, and exergoenvironmental analysis have been utilized for a more precise investigation and better evaluation of the system. The analysis of entropy production, irreversibility, and measurement of energy system deviations in ideal operational conditions can be easily achieved by employing the second law of thermodynamics to more accurately investigate and evaluate the energy systems. Equation (6) shows the exergy balance [31]:

$$Ex_Q + \sum_i m_i ex_i = \sum_e m_e ex_e + Ex_w + Ex_D, \tag{6}$$

Where Ex_Q, Ex_w, Ex_D, ex_i, and ex_e correspond to the exergy caused by heat transfer, exergy caused by power transfer, exergy destruction, and exergy caused by mass flow rates of the inlet and outlet streams, respectively. Other necessary equations for this analysis are mentioned in reference [31].

Exergoeconomic and exergoenvironmental analyzes have been reviewed to check the economic and environmental performance of the system, and its balance is as follows [32]:

$$C_Q + \sum_{in}(c.Ex)_{out} + Z_k = C_w + \sum_{out}(c.Ex)_{out}, \tag{7}$$

$$B_Q + \sum_{in}(b.Ex)_{out} + Y_k = B_w + \sum_{out}(b.Ex)_{out}, \tag{8}$$

Z_k, b, c, and Y_k respectively represent the investment cost of each piece of equipment, environmental impacts of the flow, flow cost, and environmental impacts of each piece of equipment over its lifetime. Other necessary equations have been mentioned in reference [32]. The constants used in this study are: an interest rate of 10%, a maintenance factor of 1.06, and a 20-year lifespan for the power plant and operating hours considered are 3500 hours for PTC, 6000 hours for wind, and 8000 hours for other equipment [32]. In addition, references [12, 32] have been used for capital investment cost and equipment weights in economic and environmental calculations. Environmental analysis using LCA. LCA, as a technique, searches, evaluates, and examines the environmental impacts of a product or equipment from manufacturing, transportation, use, disposal, and important environmental impact aspects are analyzed.

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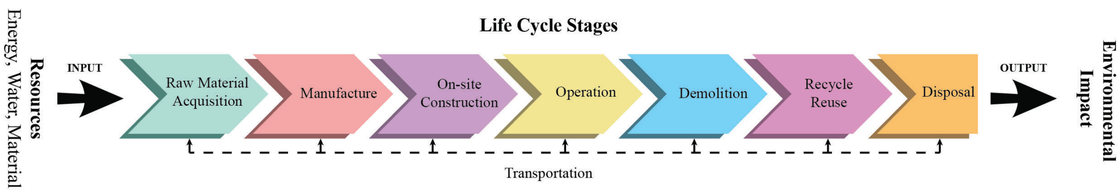


Figure. 2. Life cycle Assessment stages [33]

4. Results

Figure (3) shows the results of the energy analysis of the proposed system in a block form. In this figure, it is possible to observe the relationship between the different parts of the proposed system and the exchanged energies within the system.

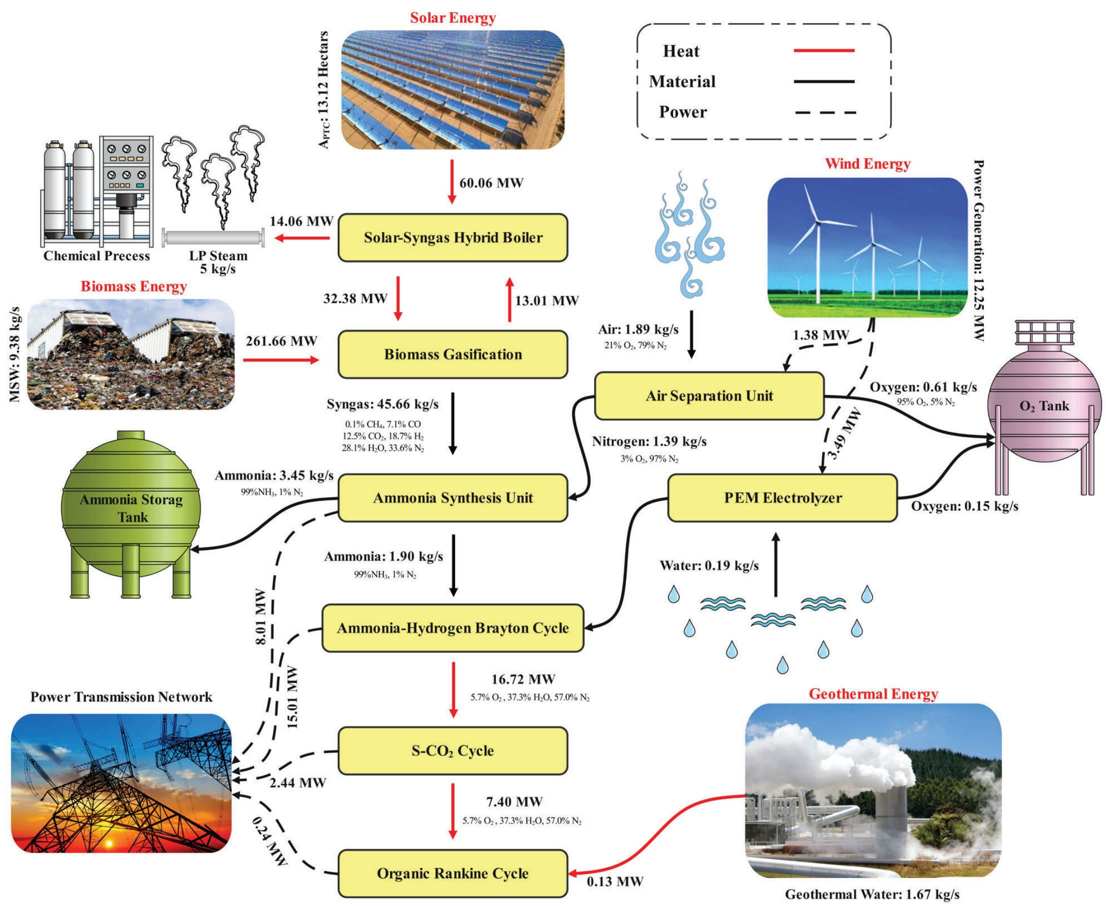


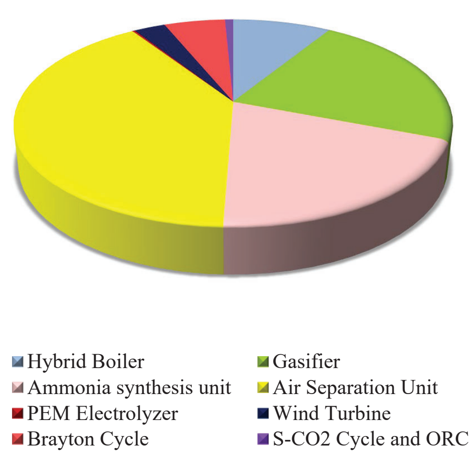
Figure. 3. The block diagram of the proposed system.

For a more detailed analysis of the proposed system, energy, exergy, economic and environmental analyzes have been performed on the system and its results have been discussed. The highest exergy efficiency is related to the expander equipment for power generation from syngas. The lowest exergy efficiency is related to the wind turbine farm. The highest investment costs in the studied system are related to the solar farm with a cost of 0.46 $/s and the wind farm with a cost of 0.22 $/s, respectively. The highest environmental impacts have been caused by the S-CO_2 turbine, and it is necessary to modify this equipment to reduce the environmental impacts. According to Table (1) which shows the 4E results on the proposed system, it can be stated that the Net power generation, Total exergy destruction, Overall polygeneration exergy efficiency, Total cost rate of polygeneration system, and Total environmental impact rate of polygeneration system are 17.93

(MW), 553.31 (MW), 38.53 (%), 3222.35 ($/h), and 53.16 (Pts/kWh), respectively. The pie diagrams in Figures (1a), (1b), (1c) represent exergy destruction, cost destruction, and environmental impact destruction of the system, respectively. It is clear that the ASU is more destructive in terms of exergy destruction, cost destruction, and environmental impact compared to other parts of the system. One reason for this is that the system involves deep cooling processes which require high energy consumption. Therefore, the exergy destruction, cost destruction, and environmental impact of this unit are very high, and corrective measures need to be taken to improve the system. The ammonia production unit has high exergy destruction after ASU due to high energy consumption and high losses. It is necessary to recover these losses in the system to reduce exergy destruction. In the gasification unit, because many chemical reactions occur and the production of entropy is high, its exergy destruction is also significant. The use of solar energy for the boiler has reduced the environmental impact of the equipment, but on the other hand, it has increased the cost of destruction of this equipment. The reason for the significant amount of exergy destruction, cost, and environmental impact in the Brayton cycle is the presence of chemical reactions and the release of a large amount of energy in the combustion chamber. Improvements must be made in the direction of improving this system. Wind turbines have a noticeable level of exergy destruction, but it is well observed that in Figures (1b) and (1c), the destruction cost and destruction environmental impact of this unit is minimized as much as possible. This shows that wind farm can be very effective in reducing costs and environmental impacts.

Table 1. overall result of 4E analysis of the proposed system.

Parameters	value
Net power generation (MW)	17.93
Net ammonia flow rate production (ton/day)	297.86
Mass flow rate of LP steam generation (kg/s)	5
Mass flow rate of oxygen generation (ton/day)	52.30
Overall polygeneration energy efficiency (%)	31.33
Total exergy destruction (MW)	553.31
Overall polygeneration exergy efficiency (%)	38.53
Total cost rate of polygeneration system ($/h)	3222.35
Total environmental impact rate of polygeneration system (Pts/h)	53.16
Levelized cost of electricity ($/kWh)	0.18
Levelized environmental impact of electricity (Pts/kWh)	0.003
MSW mass flow rate consumption (kg/s)	9.38
Geothermal mass flow rate consumption (kg/s)	1.67
Number of wind turbines (model: LTW77)	35
Area of PTC (model: ET-100) in the solar field (Hectares)	13.12



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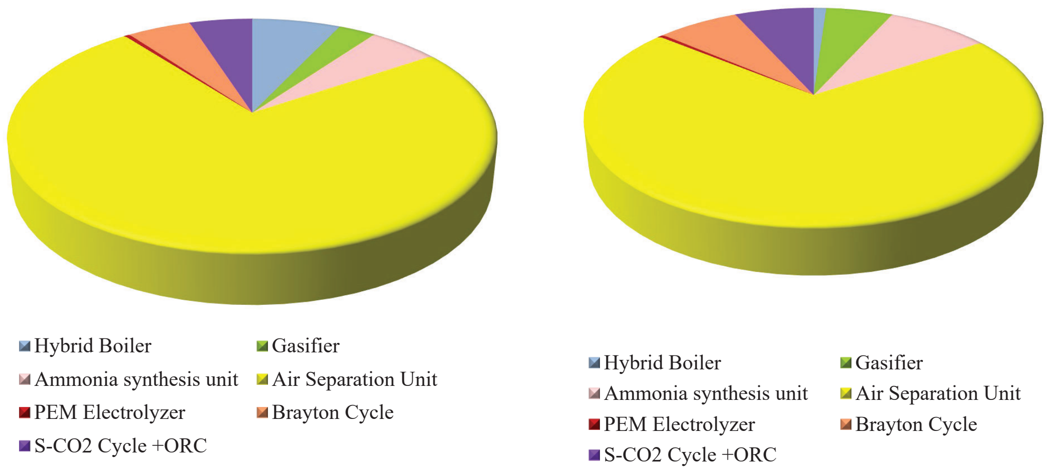
(a)



(c) (b)

Figure. 4. (a) Exergy Destruction, (b) cost destruction, and (c) environmental impact destruction Contributions of all parts in the proposed polygeneration system

5. Validation

The thermodynamic validation of the proposed system, which includes the Brayton cycle, S-CO_2 cycle, ORC, ammonia production, PEMEC, PTC, wind turbine, and gasification sections, has been verified by credible articles. It should be noted that the cases of PEMEC and gasification have been validated in the work of Mousavi Rabeti et al [12]. and PTC has also been validated in the research conducted by Khoshgoftar Manesh et al [30]., who are among the authors of this study. It has been refrained from including them due to limitations in this section. In addition, the cases of the S-CO_2 cycle, ORC, Brayton cycle, and wind turbine have been validated by modeling in MATLAB software, and their results have been validated with the articles of [23, 34-36]. Ammonia production has been simulated in Hysis software and validated with the article by Ishaq et al [22]. The performed validations have been compared with articles and their results have the least errors, so the performed validation is correct. The average validation error has been reported to be below 5%.

6. Conclusions

This article has presented a new polygeneration system with the driver of solar-biomass-wind-geothermal energy to produce power, heat (steam), and ammonia for the city of Tehran in Iran. MSW gasification has been used for ammonia synthesis. A part of produced ammonia along with hydrogen has also been used as biofuel to produce electricity in Brayton, supercritical CO_2, and organic Rankine cycles. Modeling of the proposed system has been done using energy, exergy, exergeoeconomic, and exergoenvironmental (4E) analyses. The general results of polygeneration system modeling show that this system has an average energy and exergy efficiency of 31.33% and 38.53%. The results of the economic and environmental analysis show that the overall cost rate and environmental impacts rate of the entire system are 3222.35 $/h and 53.16 Pts/h, respectively. Other main results are as follows:

- Production of ammonia and process steam is equal to 297.86 ton/day and 5 kg/s, respectively.
- Using biomass and solar energy to produce products in the proposed system is more than other energies.
- The most destruction of exergy, destruction of costs, and destruction of environmental impacts is related to the air separation unit.
- The highest investment cost is related to the solar and wind field sectors.

In the end, this system can be integrated with other energy systems, such as a variety of thermal desalination systems, in order to have more flexibility in producing products while having low environmental impacts. Conducting more investigations including dynamic analysis and optimization can better evaluate the performance of such a system.

Acknowledgments

This research has been co-funded by ERDF funds, INTERREG MAC 2014-2020 programme, within the ACLIEMAC project (MAC2/3.5b/380). No funding sources had any influence on study design, collection, analysis, or interpretation of data, manuscript preparation, or the decision to submit for publication.

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