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Biomass driven polygeneration systems: A review of recent progress and future prospects

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ABSTRACT

Biomass is the most widely used renewable energy source which is highly appreciated due to its high availability and non-intermittent nature. Considering problems such as reduction of fossil fuels, global warming, and emission of greenhouse gases, lack of attention to the existing situation may cause irreversible damage to the future of the planet. In addition to using renewable energy sources, improving the efficiency of systems will also be helpful. Polygeneration systems play an important role in increasing efficiency and reducing pollution. So, the use of biomass in polygeneration systems seems to be a great approach for sustainable development. Recent studies on biomass-based polygeneration systems have focused on how to use biomass and integrate diverse subsystems to achieve the best performance from energy and exergy viewpoints. The present paper reviews biomass-based systems, and the parameters affecting the performance of these systems. The literature review shows that the high exergy destruction rate in the gasifiers is the most frequent problem among recent articles. In addition, despite the advantages of anaerobic digestion process, the number of studies conducted on the use of this method for biomass conversion is small. In the end, results, limitations, and future outlooks of these systems are discussed.

1. Introduction

1.1. Critical challenges

The most critical issues that the World faces today are energy and environment. Global energy consumption is sharply increasing, due to the change in living standards and continuous growth of population, however meeting this need with traditional methods threatens the environment. Contrary to the increase in energy demand throughout the World, fossil fuels, is presently more troublesome to reach since of the pandemic, transport or reciprocal relations, etc (Köse et al., 2022). According to the International Energy Agency (IEA) reports, 74 % of global electricity comes from fossil fuel-based power plants (Sorgulu and Dincer, 2021); However, regular plants can only convert approximately 30 % of the input fuel energy into electricity (Dincer and Acar, 2018), then, the remainder of the energy is wasted and the resulting pollution harms the environment.

Single generation systems create a lot of energy losses and lead to economic and environmental damages. Cogeneration systems are a group of energy systems that can generate electricity and heat simultaneously from a single energy source and consequently improve energy efficiency and control environmental pollution. Another type of energy system is tri-generation systems which are generally utilized for power, heating, and cooling generation. Furthermore, an upgraded version of these systems that generates more products, is presented as multi-generation systems. The solution that has attracted researchers' attention for this aim, is the study of polygeneration power plants, which seems to be a key solution for a sustainable future. Polygeneration systems are able to generate two or more energy products simultaneously in a single integrated process (Rong and Lahdelma, 2016). Such plants minimize losses, increase energy efficiency, and reduce negative environmental impacts considerably, by the integration of numerous subsystems (Gholamian et al., 2018). Therefore, the polygeneration systems have a lot of advantages, including reduction in greenhouse gas emissions, energy supply with lower cost, reduction in energy losses, and an increase in efficiency. These systems are also able to make an effective

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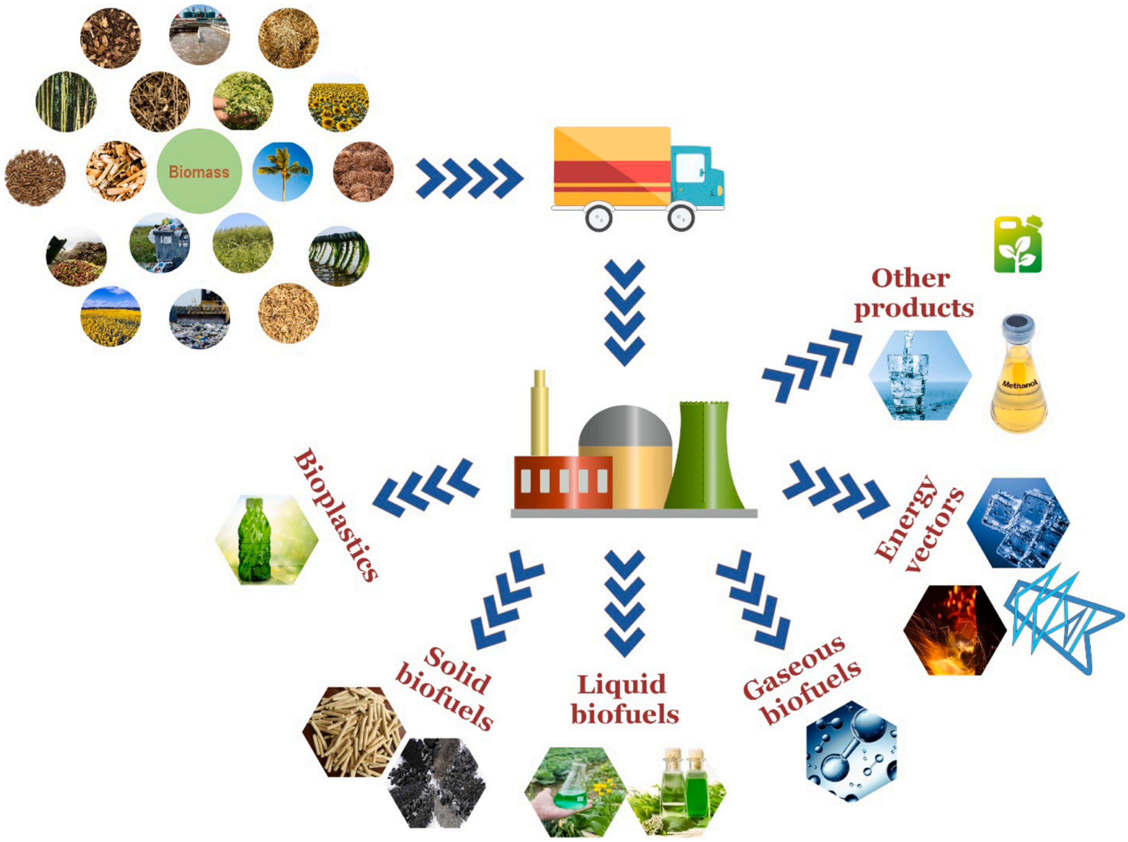


Fig. 1. Schematic diagram of the biomass-based polygeneration system.

use low-grade heat (Murugan and Horák, 2016). It is claimed that multi-generation systems can reduce 950 Mton/year of CO_2 emissions by 2030 (Cho et al., 2014).

Furthermore, due to the reduction of fossil fuel sources and the damages affected to the environment through the use of these fuels, renewable energy sources have been considered as an attractive alternative during the past few years. Renewable energies, due to their contribution to combating global warming and reducing pollution, play an influential role in sustainable development (Calise et al., 2018).

With current preludes, it can be concluded that renewable energy-based polygeneration systems play a significant role in solving challenges related to energy and environment. However, more renewable energies like solar energy usually have intermittent nature (Dincer and Acar, 2018); that is, they may not meet the needs of all 24 h of a day or all days of the year or even in all regions of the World (Guo et al., 2018).

Biomass is a renewable energy source; it is the most widely used renewable energy source for heating in Europe (Segurado et al., 2019) due to its broadness and high availability compared to other renewable energy sources (Dincer and Acar, 2018). Another attraction of Biomass as an energy source is that recycling bio-waste is essential for circular economy and sustainable development (Villarini et al., 2019). European Waste Framework Directive is committed to managing waste disposal in a way that does not damage terrestrial and aquatic ecosystems (Soltanian et al., 2022).

Lastly, it can be stated that biomass-based polygeneration systems have gained particular importance because of producing energy and some valuable products by consuming wastes.

1.2. Biomass-based polygeneration systems

The energy source utilized in polygeneration systems can include renewable and non-renewable energy sources. Due to the importance of renewable energy sources in utilization and also their limitation in intermittent nature, as previously mentioned, Biomass was introduced as one of the main energy sources around the World. According to the European Union's definition of biomass in 2001, biomass is "*The biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste*" (https://www.eea.europa.eu/help/glossary/eea-glossary/biomass, Accessed). Biomass has been known as a cleaner and greener energy source and has gained the highest dispatchability rating among other renewable energy sources (Dincer and Acar, 2018). Unlike fossil fuels, the carbon that biomass-based energy production release is the same carbon that biomass has captured from the air; therefore, it is assumed that bio-fuels add no pure carbon to the atmosphere and, as neutral fuels, have a less environmental impact (Taheri et al., 2021). Global Bioenergy Statistics reported that biomass contribution to primary energy supply in 2017 was about 55.6 EJ. It is also estimated that by 2030, nearly 50 % of the global energy demand will be supplied by renewable energies, especially biomass (Tezer et al., 2022). Therefore, it can be concluded that biomass-based polygeneration systems combine the benefits of increased efficiency, energy conservation, and environmental compatibility, with the benefits of using a renewable source of energy that compensates the intermittent nature of renewable energies (Cotana et al., 2022). The schematic diagram of the biomass-based polygeneration system and its products are depicted in Fig. 1 (Cotana et al., 2022; Pal et al., 2022).

The analysis of polygeneration systems from a thermodynamic viewpoint provides the possibility of quantitative comparison of systems and helps to identify and improve the sources of losses. Therefore, it is possible to design and develop systems with maximum efficiency and minimum pollution emission with economic savings (Dincer and Acar, 2018). More details about system analysis are discussed below.

Table 1

Main equations for energy systems modeling (Soltanian et al., 2022; Aghbashlo et al., 2021; Auracher, 1996).

Description	Formula	Notation (s)
Mass balance in steady-state condition	$\sum_i \dot{m}_i = \sum_e \dot{m}_e$	$\dot{m}$: mass flow rate (kg/s), subscript *i*: inlet stream, subscript *e*: exit stream
Energy balance in steady-state condition	$\sum_j \dot{Q}_j + \sum_i \dot{m}_i h_i = \dot{W} + \sum_e \dot{m}_e h_e$	$\dot{Q}$: heat transfer rate (kW), $\dot{W}$: work rate (kW), *h*: specific enthalpy (kJ/kg), subscript *j*: numerator
Entropy balance in steady-state condition	$0 = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_{gen}$	*s*: specific entropy (kJ/kg K), $\dot{S}_{gen}$: rate of entropy generation (kJ/kg)
Exergy balance in steady-state condition	$\sum_j \dot{E}x_{q_j} + \sum_i \dot{m}_i ex_i = \dot{W} + \sum_e \dot{m}_e ex_e + \dot{E}x_d$	*Ex*: Total specific exergy, $\dot{E}x$: exergy rate, subscript *q*: thermal energy, subscript *d*: destruction
Exergy of thermal energy	$\dot{E}x_{q_j} = \dot{Q}_j(1 - \frac{T_0}{T_j})$	*T*: temperature (K), subscript *0*: reference state
Total specific exergy of a stream	$ex = ex^{ph} + ex^{ch} + ex^{ke} + ex^{pe}$	Superscripts *ph*: physical, *ch*: chemical, *ke*: kinetics, and *pe*: potential
Specific physical exergy of a pure stream	$ex^{ph} = h - h_{\circ} - T_{\circ}(s - s_{\circ})$	–
Specific physical exergy of a mixed liquid stream	$ex^{ph} = C\left(T - T_{\circ} - T_{\circ} Ln\left(\frac{T}{T_{\circ}}\right)\right)$	*C*: specific heat capacity (kJ/kg K)
Specific physical exergy of a mixed gaseous stream	$ex^{ph} = C\left(T - T_{\circ} - T_{\circ} Ln\left(\frac{T}{T_{\circ}}\right)\right) + RT_{\circ} Ln(\frac{P}{P_{\circ}})$	*R*: gas constant (kJ/kg K)
Specific chemical exergy of a mixed fluid stream	$ex^{ch} = \sum_k \frac{1}{y_k M_k}\left(\sum_k y_k \overline{ex}^{\circ}{}_k + \overline{R}T_0 \sum_k y_k Ln(y_k)\right)$	$\overline{ex}^{\circ}$: standard chemical exergy (kJ/mol)
Specific kinetic exergy of a stream	$ex^{ke} = \frac{1}{2 \times 1000} V^2$	V: velocity (m/s)
Specific potential exergy of a stream	$ex^{pe} = \frac{1}{1000} gz$	*g*: gravitational acceleration constant (m^2/s), *z*: height (m)
Exergy efficiency	$\varphi = \frac{\dot{E}x_e}{\dot{E}x_i} = 1 - \frac{\dot{E}x_d}{\dot{E}x_i}$	φ: universal exergy efficiency (%)
Cost balance equation	$\sum_j c_j \dot{E}x_{q,j} + \sum_i c_i \dot{m}_i ex_i + \dot{z} = c_w \dot{W} + \sum_e c_e \dot{m}_e ex_e$	*c*: specific cost of exergy (USD/kJ), $\dot{z}$: investment cost rate (USD/s), subscript *w*: work
Environmental impact equation	$\sum_j b_j \dot{E}x_{q,j} + \sum_i b_i \dot{m}_i ex_i + \dot{Y} = b_w \dot{W} + \sum_e b_e \dot{m}_e ex_e$	*b*: specific environmental impact of exergy (mPts/kJ), $\dot{Y}$: environmental impact rate (mPts/s)

1.3. Thermodynamic analysis of energy systems

Due to the importance of equations and modeling methods for polygeneration systems, it is essential to use appropriate equations and innovative methods to analyze the systems. Thus, this part summarizes and presents the modeling equations. The equations presented in this section evaluate the general approach of energy systems analysis. A more detailed assessment of biomass-based systems is provided in section 3.3.

Thermodynamic analysis of polygeneration systems is generally investigated from energy and exergy viewpoints. The energy assessment is a common analysis which is used to study the system from the first law of thermodynamics viewpoints and energy conservation. In system investigations, however, exergy analysis has an advantage over energy analysis (Khaliq and Dincer, 2011), which provides information about energy quality to assist researchers in offering solutions for system performance increase by the proper understanding of their losses, origin, and causes (Dincer and Acar, 2018). Exergy of a thermodynamic system is the maximum amount of theoretical useful work that can be obtained as the system is brought to equilibrium with the environment and includes physical exergy (results from the deviation of the temperature and pressure of the system from its environment), chemical exergy (results from the deviation of the system composition with environment composition), kinetic exergy (results from the speed of the system relative to the environment), and potential exergy (results from the height of the system relative to the environment). In addition, physical exergy itself includes mechanical exergy (depending on system pressure) and thermal exergy (depending on system temperature). Also, chemical exergy includes reactive exergy (related to chemical reactions) and nonreactive exergy (related to non-reaction processes such as expansion and integration) (Tsatsaronis, 2007). Other approaches called the exergo-economic and exergo-environmental analyses have also been conducted by researchers for system investigation, which combines economic and environmental principles with exergy concept to provide the information that cannot be accessed by exergy and economics/environmental analyses alone (Aghbashlo et al., 2021; Auracher, 1996). The main equations for systems modeling and their thermodynamic analysis are depicted in Table 1 (Soltanian et al., 2022; Aghbashlo et al., 2021; Auracher, 1996). An important point about the equations related to this table is that standard/specific chemical exergy of different materials is available in different forms, some data are directly available from sources such as Bejan et al (Auracher, 1996)., some of them (inorganic substances) can be calculated using the relations that are presented in Table 1, and the essential formulas for the calculation of the standard chemical exergy of organic substances have been evaluated and discussed in literatures (Aghbashlo et al., 2021).

1.4. Contribution and objective of this work

The present work aim is to review the articles in the field of biomass-based systems that have been studied recently. The number of studies in this field is numerous, and the present study has only investigated the systems that provide energy just from one source, that is, biomass. Systems whose energy sources are hybrid have not been investigated in the current paper. According to the authors' information, such a review has not been conducted so far, especially in recent years. Among the review articles that have investigated similar issues, these cases can be mentioned: Guo et al. (2018). in a review paper investigated systems with hybrid energy sources. Their work investigates the use of hybrid resources in plants and their especial focus is not on the biomass energy source. Wegener et al., (2018) proposed biomass based combined cooling, heating, and power (CCHP) systems in small-scale applications. They have only reviewed the small scale CCHP systems, and have not conducted a review on the other polygeneration plants. In a systematic literature review, Soltanian et al. (2022) inspected municipal solid waste treatment systems. Their research has done a comprehensive review on the solid waste-based plants, but has not investigated systems based on other biomasses. In a recent review paper, Tezer et al. (2022) reviewed biomass gasification-based systems and offered an approach for hydrogen-rich syngas production. In their review paper, the focus is on the gasification process and other biomass-based plants are not mentioned. Cotana et al. (2022) studied biomass-based systems more

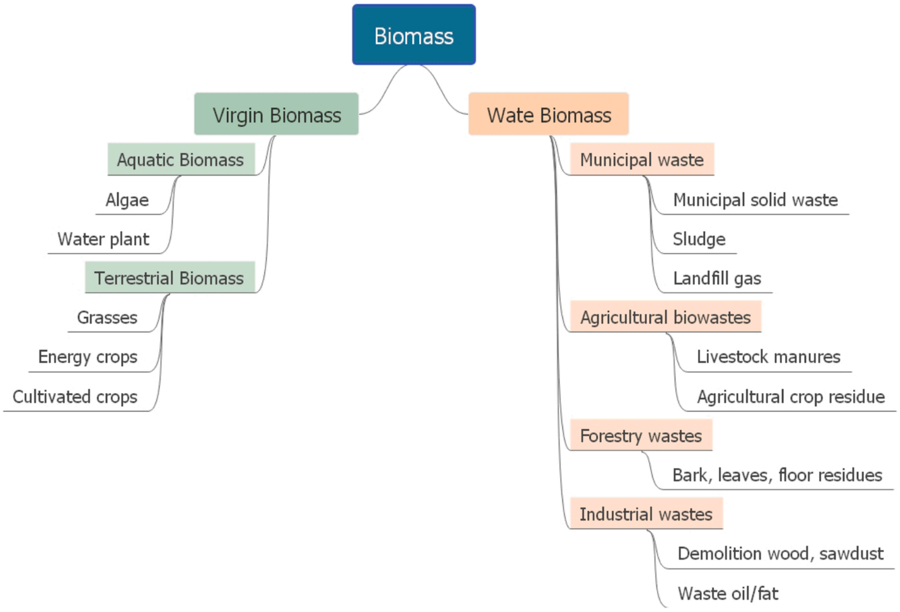


Fig. 2. Biomass classification.

Table 2
Some of the properties of different types of biomasses.

Biomass	Composition (wt%, dm)						LHV (kJ/kg)	HHV (kJ/kg)	Ref
	C	H	N	O	S	Ash			
Bagasse	48.64	5.8	0.16	37.38	–	8.02	7650	–	(Bamisile et al., 2020)
Cladophora glomerata	34.4	5	5.2	18.6	3.2	34.5	–	–	(Safari and Dincer, 2022)
Coffee husk	46.8	4.9	0.6	47.1	0.6	1	16540		(Mehrpooya et al., 2018)
Corn straw	44.73	5.85	0.60	41.15	0.02	7.65	32500	–	(Ishaq and Dincer, 2021a)
Cotton stalk	47.05	5.35	0.65	40.77	0.21	5.51	–	–	(Roy et al., 2020a)
Date pits	50.84	6.83	4.45	37.88	0	0.98	25300	–	(Ghiat et al., 2020)
Demolition wood	46.30	5.39	0.57	34.45	0.12	13.12	–	16680	(Yilmaz et al., 2019)
Fawl manure	50.20	6.5	5.20	34.6	–	–	–	–	(Ghaffarpour et al., 2018)
Furniture waste	49.87	5.91	0.29	40.29	0.03	3.61	–	17200	(Zaman and Ghosh, 2022)
Maize Silage	33.71	4.47	11.16	16.86	–	33.80	–	–	(Bamisile et al., 2019)
Municipal solid waste	47.6	6	1.2	32.9	0.3	12	–	19567.66	(Sadeghi et al., 2018)
Olive pits	48.84	6.22	0.37	43.46	0.021	–	16200	–	(Yuksel et al., 2020)
Pine bark	55.49	5.56	0.17	37.74	0.09	0	–	–	(Roy et al., 2020a)
Pine sawdust	52.28	5.20	0.47	40.85	–	–	–	–	(Ghaffarpour et al., 2018)
Poplar	50.18	6.06	0.60	40.43	0.03	2.70	18580	–	(Li et al., 2021)
Poplar wood chips	50.9	6.04	41.9	0.17	0.09	0.9	–	18600	(Li et al., 2022)
Poultry litter	37.50	5.5	4.7	29.4	–	21	–	–	(Sevinchan et al., 2019)
Rice husk	38.83	4.75	0.52	35.47	–	20.43	15000	–	(Bamisile et al., 2020)
Sawdust	49.2	5.99	0.82	42.98	0.03	0.98	–	18110	(Li et al., 2020)
Sawdust wood	47.96	6.11	0.34	44.91	0.09	0.59	17208	18412	(Onder et al., 2020)
Sewage sludge	37	4.5	3.3	19.5	0.65	30	18000	–	(Cartmell et al., 2006)
Straw	49	6	0.8	44	0.2	0	–	–	(Roy et al., 2020a)
Torrefied pellets	56	5	38.6	0	0.4	0	–	–	(Roy et al., 2020a)
Wood chip	51.19	6.08	0.2	41.3	0.02	1.16	–	19900	(Mehrpooya et al., 2018)

from the chemical aspects not the exergy ones.

Therefore, an article that reviewed biomass-based polygeneration systems from the perspective of energy and exergy and did not limit the selection of articles to a specific category of biomass conversion methods was not found in the literature. While considering the high number of articles that have been published on this topic, a single and comprehensive platform is necessary to summarize these studies. The current study reviews the developed biomass-based systems that have been recently studied from an exergetic viewpoint. This study has been conducted to investigate the innovations, challenges, and progress of these systems carefully, and to clarify the way for researchers to continue their studies in this field.

The present paper is ordered in 5 sections. The first section presents an introduction and the main concepts related to this study review. In Section 2, biomass as the only source of energy for these systems is described, and its conversion processes is discussed briefly. In Section 3, an overview of biomass-based polygeneration systems has been carried out. A structured four-step method was used to select the final sample of articles for further investigation in this section. First of all, the search string was formulated based on different combinations of the keywords "exergy" and "biomass" and "polygeneration" as the main keywords of this work. In the second step, the Scopus database was selected for article collection. According to the considered criteria, only recently published peer-reviewed articles in the English language were included. Therefore, other document types, such as notes, editorials, and letters, were excluded from the extracted samples in this step. Also In the third step, the articles were filtered through screening the titles and abstracts to select the papers with high relation to our research. In the end, 84

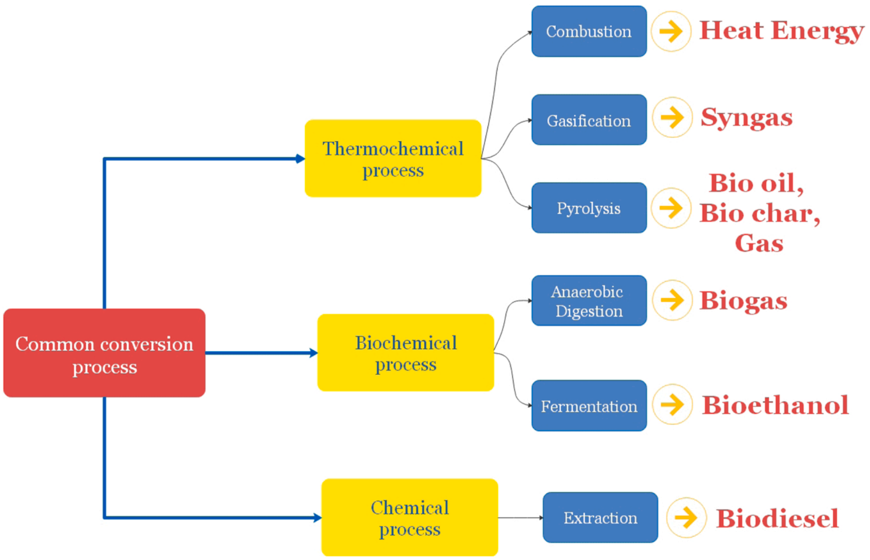


Fig. 3. Common biomass conversion methods.

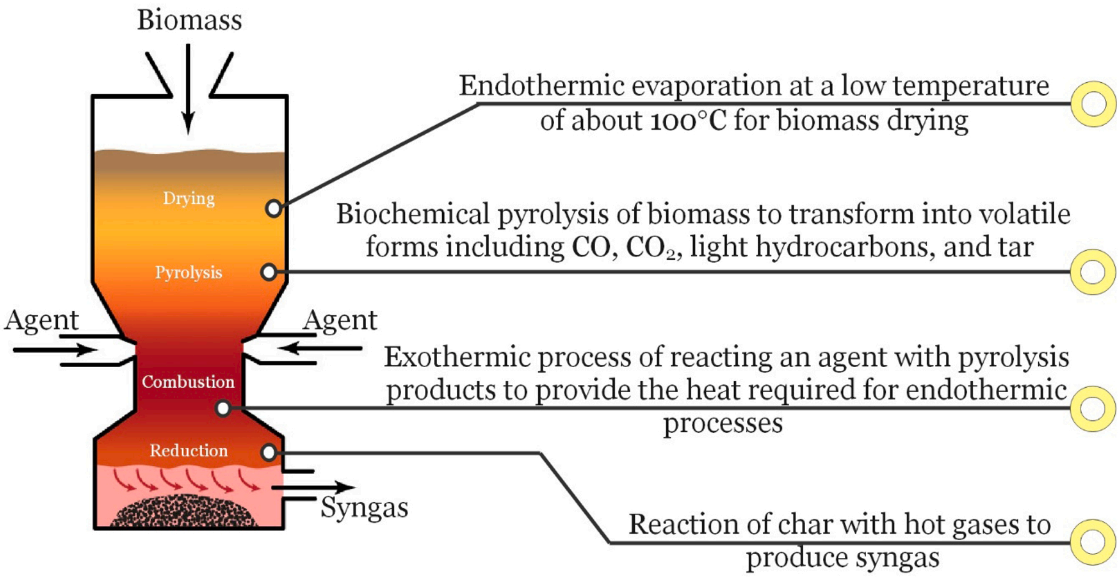
Table 3
Main gasification reactions (Villarini et al., 2019; Safarian et al., 2022).

Description	Equation	ΔH (kJ/kmol)
Combustion	$C + O_2 \rightarrow CO_2$	-394
Carbon partial combustion	$C + 0.5O_2 \rightarrow CO$	-111
Boudouard	$C + CO_2 \rightarrow 2CO$	+172
Water-gas	$C + H_2O \rightarrow CO + H_2$	+131
Methanation	$C + 2H_2 \rightarrow CH_4$	-75
CO partial combustion	$CO + 0.5O_2 \rightarrow CO_2$	-283
Hydrogen combustion	$H_2 + 0.5O_2 \rightarrow H_2O$	-242
Water-gas shift	$CO + H_2O \rightarrow CO_2 + H_2$	-41
Steam reforming of methane	$CH_4 + H_2O \rightarrow CO + 3H_2$	+206
H_2S formation	$H_2 + S \rightarrow H_2S$	-20.2
NH_3 formation	$3H_2 + N_2 \rightarrow 2NH_3$	-46
HCl formation	$H_2 + 2Cl \rightarrow 2HCl$	-92.31

articles was selected as the final papers by a more in-depth reading of the full text. In the continuation of this section, the impact of effective parameters on this category of systems has been discussed in detail. The required tables for summarizing the characteristics of the systems are also provided. In Section 4, a general overview and summary are done on mentioned cases, and the main points are highlighted. The challenges that such systems face and the future perspective are discussed along with the existing gaps in the studies. Finally, in Section 5, the main results of the current article are presented.

2. Biomass

According to the IEA definition, renewable energy is a type of energy that comes from natural processes and resources that are continuously replaced (Dincer and Acar, 2015). Accordingly, biomass is considered a renewable energy source. It is the third most widespread source of energy in the world after coal and oil. It has many advantages such as high availability, easy storage, and carbon neutrality, because CO_2 arising from biofuel combustion is almost equal to CO_2 captured by biomass during its life (Safarian et al., 2022). Furthermore, biomass waste recycling, leads to the production of valuable products, while compensating the environmental impacts due to unprincipled waste disposal.



Endothermic evaporation at a low temperature of about 100°C for biomass drying

Biochemical pyrolysis of biomass to transform into volatile forms including CO, CO_2, light hydrocarbons, and tar

Exothermic process of reacting an agent with pyrolysis products to provide the heat required for endothermic processes

Reaction of char with hot gases to produce syngas

Fig. 4. A schematic diagram of a downdraft gasifier with a throat type.

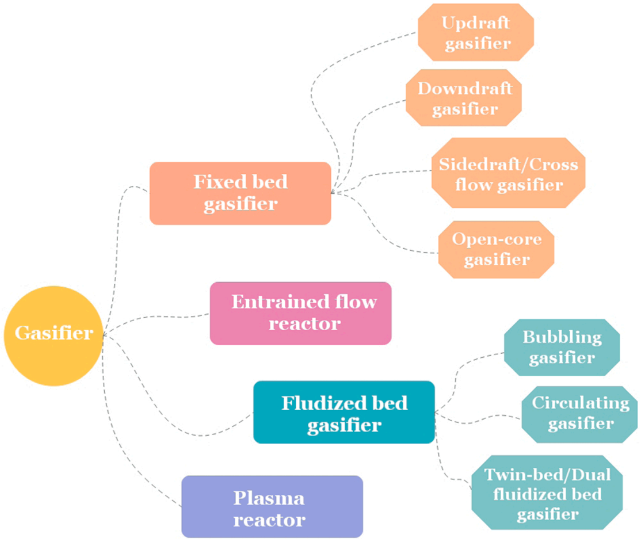


Fig. 5. A general classification of gasifiers.

Biomass includes a wide range of materials, that forestry remnants, municipal waste, and industrial waste, respectively are largest biomass source for energy production (Tezer et al., 2022; Mehrpooya et al., 2018).

Biomass classification is carried out according to different standards, but in a general classification, biomass can be classified into two categories: waste biomass and virgin biomass (Tezer et al., 2022). Fig. 2 shows the details of this classification.

Feeding polygeneration systems with biomass is one of the best solutions to increase the sustainability of systems. Some of the most essential properties of biomass that are considered in biomass selection for systems include availability, moisture content, bulk density, elemental composition, available ash content, and heating value (Villarini et al., 2019). Table 2 lists some of these properties for different types of biomasses that have been used in recent polygeneration systems.

Biomass must be pretreated by processes before entering the system. The main process that biomass goes through is a stage called conversion. During this stage, biomass is converted into biofuel to produce energy and other products. The most common biomass conversion methods are shown in Fig. 3 (Segurado et al., 2019; Aghbashlo et al., 2021; Ong et al., 2019).

Within the biochemical processes, anaerobic digestion is a more preferable method. Anaerobic digestion is a process that is carried out in the absence of oxygen and converts decomposable organic matter into biogas and other energy-rich organic compounds. The cost of this process is less, but the required time is significantly longer than other methods (Liew et al., 2022; Khanh Nguyen et al., 2021). In general, among all the conversion methods, gasification is highly accepted, and so it is attracted the researchers' attention. The conversion of the solid fuel into the gaseous fuel such as syngas through partial oxidation of

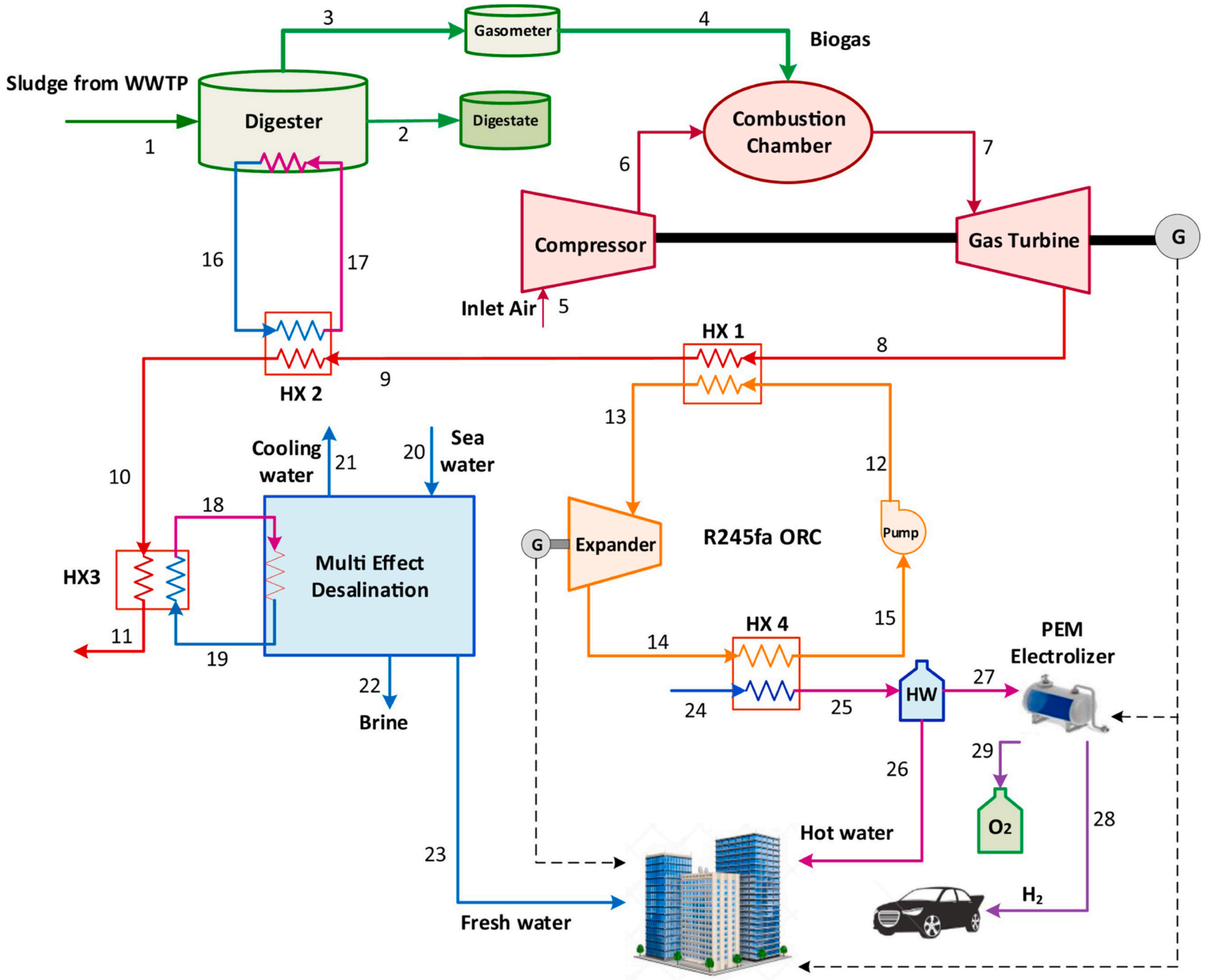


Fig. 6. A schematic of the cycle modeled by Safari et al. (adapted from Safari and Dincer (2019)).

Table 4
Summary of studies on biomass anaerobic digestion-based plants.

Biomass	Devices	Outputs	Conclusion	Ref.
Sewage sludge	proton exchange membrane electrolyzer, parallel/cross multi-effect desalination, digestion process, organic Rankine cycle, open-air Brayton cycle	Power, freshwater, hydrogen, and hot water	$\eta = 63.6$ %, $\psi = 40$ %, maximum Ex_d at Combustion chamber (2546 kW), performance ratio of multi-effect desalination system= 4.25	(Safari and Dincer, 2019)
Chicken manure and Maize silage	two-stage biomass digester, open-type Brayton cycle, Organic Rankine Cycle, single-effect absorption chiller, heat recovery, water separation unit	Electrical power, heating power, cooling power and product water from flue gas	$\eta = 72.5\%$, $\psi = 30.44$ %, maximum Ex_d at combustion chamber, maximum electrical power energy efficiency= 40.11 %, maximum cooling energy efficiency= 62.18 %, maximum heating energy efficiency= 65.35 %	(Sevinchan et al., 2019)
Chicken manure and Maize silage	two steam cycles, a gas cycle, hot water chamber, and an absorption cycle	Electricity, hot water, and cooling	$\eta = 64$ %, $\psi = 34.51$ %, maximum Ex_d at combustion chamber, biogas production is from 70,000 kg and 30,000 kg of chicken manure and maize silage respectively	(Bamisile et al., 2019)
Maize silage	a solid oxide fuel cell, a biogas digester subsystem, a cascaded closed loop organic Rankine cycle, a single effect LiBr-water absorption refrigeration cycle, and a proton exchange membrane electrolyzer	Electricity, domestic hot water, hydrogen, and cooling	$\eta = 69.86$ %, $\psi = 47.4$ %, maximum Ex_d at after-burner, 48.9 % of the input exergy is lost because of irreversibility	(Adebayo et al., 2022)
Municipal wastewater	Wastewater treatment plant, anaerobic digester, combustion chamber, absorber, electrolyzer, compressor, gas turbine, rectifier, condenser, pump, evaporator	Freshwater, power, cooling, heat, hydrogen, and oxygen	maximum Ex_d at combustion chamber in cold mode: $\eta_{opt} =$ 79.4 %, $\psi_{opt} = 49.98$ %, total annual costs of the optimal polygeneration system =US$158,000 in hot mode: $\eta_{opt} =$ 62.4 %, $\psi_{opt} = 47.58$ %, total annual costs of the optimal polygeneration system = 163,000 US$	(Ifaei et al., 2022)

biomass at high temperatures (between 500 and 1400 °C), in a range of pressures (which includes atmospheric pressure up to 33 bar), and in the presence of an agent that is usually air, oxygen, or steam is called gasification (Ruiz et al., 2013; Rajabi et al., 2019).

The gasification process has been highly accepted due to high-quality syngas production and is a cleaner technology compared to combustion and pyrolysis (Tezer et al., 2022). Syngas mainly contains H_2 and CO and smaller amounts of N_2, CH_4, H_2O, CO_2, and hydrocarbons with higher molecular weight (Segurado et al., 2019). Another importance of this process is hydrogen production. Hydrogen has the highest energy density compared to all hydrocarbon fuels and is known as a clean fuel. Gasification is recognized as a clean and efficient method for hydrogen production, because it uses a renewable energy source and is a rapid and efficient process (Safarian et al., 2022). In the gasification process for hydrogen production, steam processing causes an increase in H_2 production (Younas et al., 2022).

Gasification is conducted in a reactor called a gasifier. The main gasification reactions are presented in Table 3. A schematic diagram of a downdraft gasifier with a throat type and a description of gasification steps, including drying, pyrolysis, combustion, and reduction, is displayed in Fig. 4 (Tezer et al., 2022; Li et al., 2022). Also, Fig. 5 shows a general classification for gasifiers.

Equivalence ratio and agent type, affect the gasification process and the quality of the produced syngas (Mehrpooya et al., 2018). The equivalence ratio can be defined as the air-to-fuel ratio in the gasification process to the air-to-fuel ratio in the complete combustion process. According to the conducted studies, an increase in the equivalence ratio usually causes a decrease in system efficiency (Asadullah, 2014). In syngas production, an oxidizing agent is used, which has an essential effect on the quality and composition of the produced syngas, because it reacts with heavy hydrocarbons and produces gasses with lower molecular weight, such as H_2 and CO. The most commonly used agents are oxygen, air, and steam (Tezer et al., 2022). CO_2 utilization as an agent has also been studied. The utilization of CO_2 as an agent can have the advantage of using carbon and preventing pollution along with the efficient use of energy (Li et al., 2020).

3. Biomass-based polygeneration systems

3.1. Biomass-based plants

As discussed in detail in previous sections, biomass-based polygeneration systems, in addition to having advantages of polygeneration systems in improving the systems' efficiency, have the privilege of using a renewable energy source with high availability that can lead to sustainable development. For this reason, the present paper, have reviewed studies in the field of biomass-based polygeneration systems which provide energy from only biomass source. According to the recent review of the articles, it is found that anaerobic digestion and gasification are the most common biomass conversion methods studied in the papers. Meanwhile, this section is divided into several subsections, and each method is discussed separately; furthermore, the studies that used anaerobic digestion and gasification methods for biomass conversion simultaneously, have also been mentioned. In addition, studies that compared these two methods in their system and investigated the system behavior in each case, have been reviewed. Lastly, other related articles with different goals, have also been included. The most important information about each reviewed article and their main results are presented in the tables.

3.1.1. Biomass anaerobic digestion-based plants

Biomass anaerobic digestion is the most common conversion method among biochemical conversion methods. There are many studies in this field compared to other biochemical conversion methods, but compared to gasification, very few papers have investigated this method. Safari and Dincer (2019) designed a biomass anaerobic digestion-based polygeneration system which uses sewage sludge to produce electricity, freshwater, heat, and hydrogen. A schematic of the cycle in this article is shown in Fig. 6. The current study investigated the integration of the anaerobic digestion process with other subsystems and implemented energy and exergy analyses for the system.

Sevinchan et al. (2019) conducted a comprehensive energy, exergy, and environmental analyses on a biomass anaerobic digestion-based polygeneration system. In this system, anaerobic digestion takes place in two stages. One of the strengths of this system is the production of water from the flue gas of the system itself for agricultural purposes. This system can produce power, heating, cooling, and water using chicken

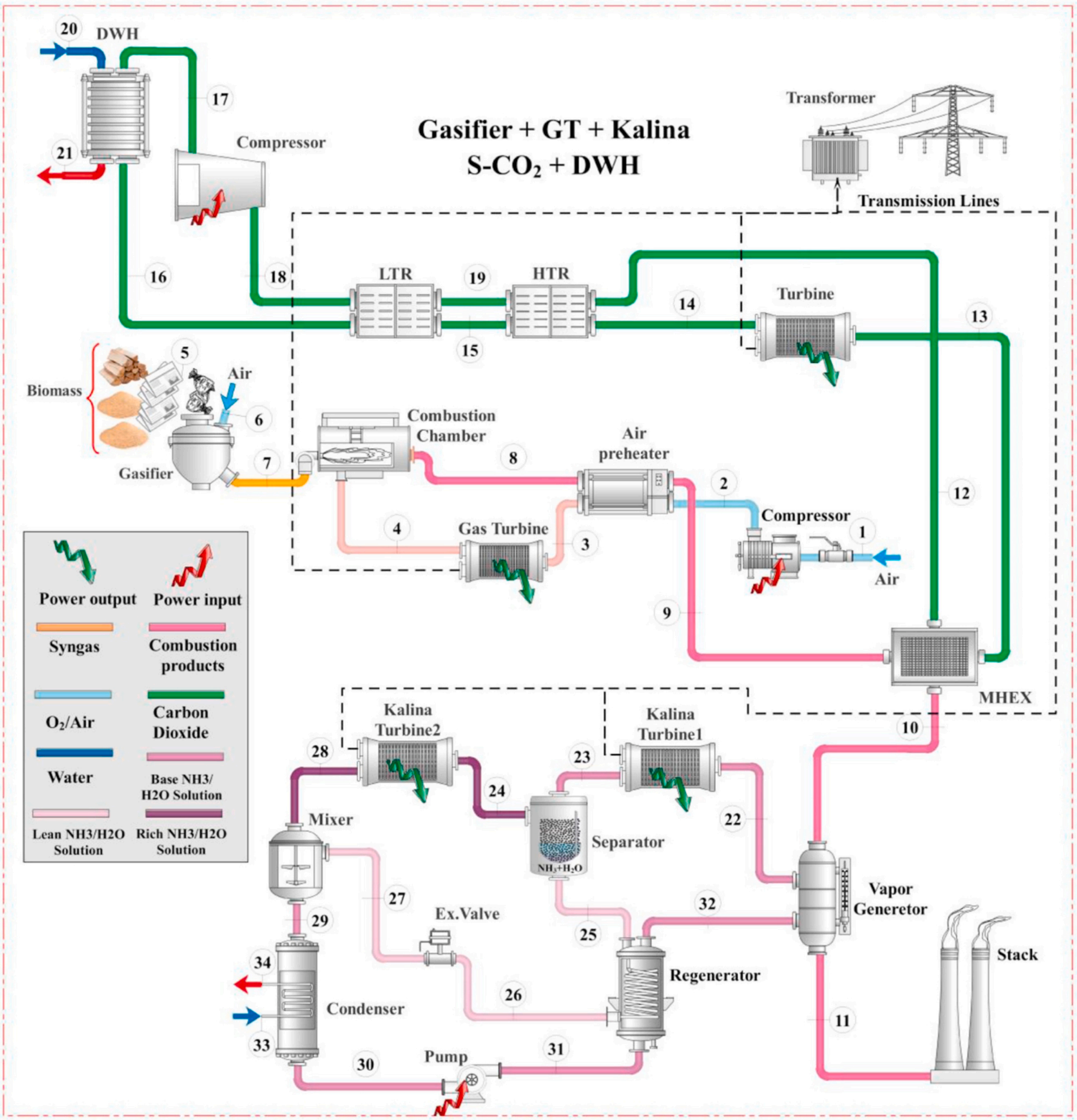


Fig. 7. A biomass gasification-based CHP system (adapted from Ji-chao and Sobhani (2021)).

manure and maize silage biomass. Using the chicken manure and maize silage biomass, Bamisile et al. (2019) designed a trigeneration system that is used for power, cooling, and hot water production. They showed that systems' exergy and energy yields in the case that only electrical energy is produced are 43.96 % and 33.34 %, respectively. In contrast, if the trigeneration system is used, the efficiency increases to 64 % and 34.51 %, respectively. Adebayo et al. (2022) proposed a biomass anaerobic digestion-based polygeneration system that uses a solid oxide fuel cell for primary power generation. This system is designed for producing power, heating, cooling, and hydrogen, and has been investigated from energy and exergy viewpoints. In the current study, the configuration and selection of subsystems are innovative; furthermore, the integration of a splitter in controlling the separation ratio of flue gas to meet specific demands is an issue that has not been investigated in previous papers. In an innovative study, Ifaei et al. (2022) presented a novel utility-free circular integration approach, which is used for modeling the first polygeneration system which is used independently of any external hot and cold devices; as a result, no excess water or energy consumption is required for cooling the system. This system works only by using biogas, so reduces the global warming potential and the risk of pollutant emissions. A summary of the properties of these articles is given in Table 4.

3.1.2. Biomass gasification-based plants

3.1.2.1. Research studies. Biomass gasification-based systems have attracted high attention compared to other biomass conversion methods-based systems. These systems are able to produce various products according to their subsystems and configuration. Single generation gasification-based power plants are interesting systems that have many environmental benefits. For example, in the power plant proposed by Gao et al. (2021) supercritical CO2 cycles, regenerative organic Rankine cycle, and steam Rankine cycle are integrated as heat recovery subsystems with biomass gasification. Their results showed that the

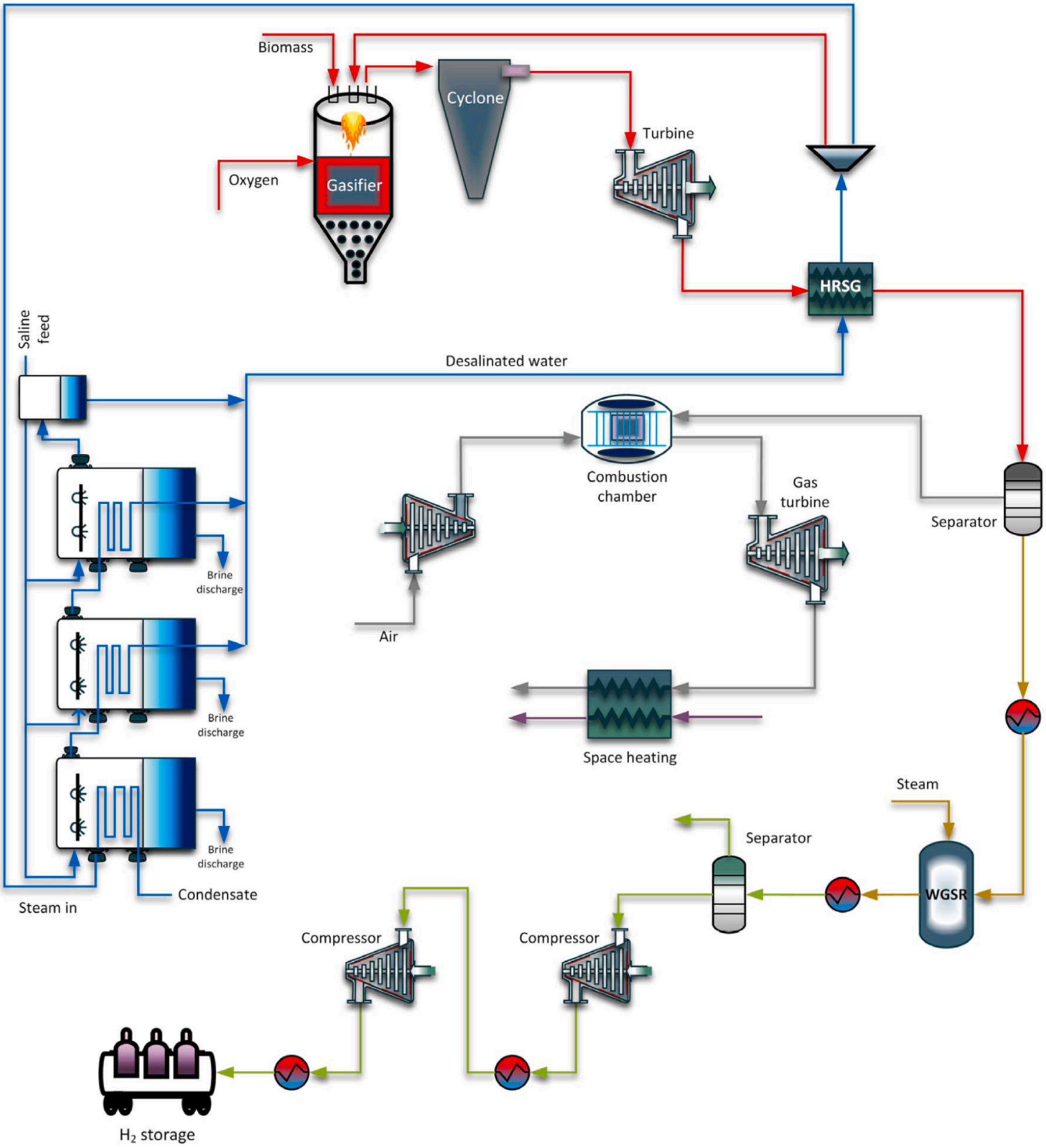


Fig. 8. A biomass gasification-based system for renewable hydrogen and energy production (adapted from Ishaq and Dincer (2021b)).

mentioned system has an exergy efficiency of 42.7 % with a power generation capacity of 7.768 megawatts. Considering that the focus of the present work is the review of polygeneration articles, it is enough to mention this case as a single generation power plant. Among the reviewed articles, there are systems that produce two products. Chattopadhyay and Ghosh (2018) designed biomass gasification-based plants which produces power and cooling. This plant uses an indirectly heated gas turbine, which has been investigated in a few studies. Cao et al (Cao et al., 2021a). used biomass gasification in the SCO_2 cycle to produce electricity and heating. Results of the economic analysis with COMFAR III software depicted the cost-effectiveness of the power plant construction. In another study, Ji-chao and Sobhani (2021) proposed a novel biomass gasification-based CHP system. This system uses a modified Kalina cycle that has a better performance compared to the Rankine cycle. The current article has also conducted a parametric study to investigate both the impact of important factors on system behavior and the feasibility of the mentioned system. Accordingly, the results have shown that the maximum exergy efficiency of the system is obtained when the air preheater’s terminal temperature difference is 262 K, and the pressure ratio of air and SCO_2 compressors is 14.5 and 4.21, respectively. The schematic of the cycle studied in this article is depicted in Fig. 7.

Due to the importance of hydrogen production as a green fuel via safe methods for the environment, many studies have been conducted in the field of hydrogen production in cogeneration systems. Moharamian et al. (2018) presented biomass gasification-based systems in which a hydrogen production unit is integrated with an externally fired combined cycle. The hydrogen obtained from the hydrogen production unit was injected into the combustion chamber of the externally fired combined cycle unit and compared its performance with the case where

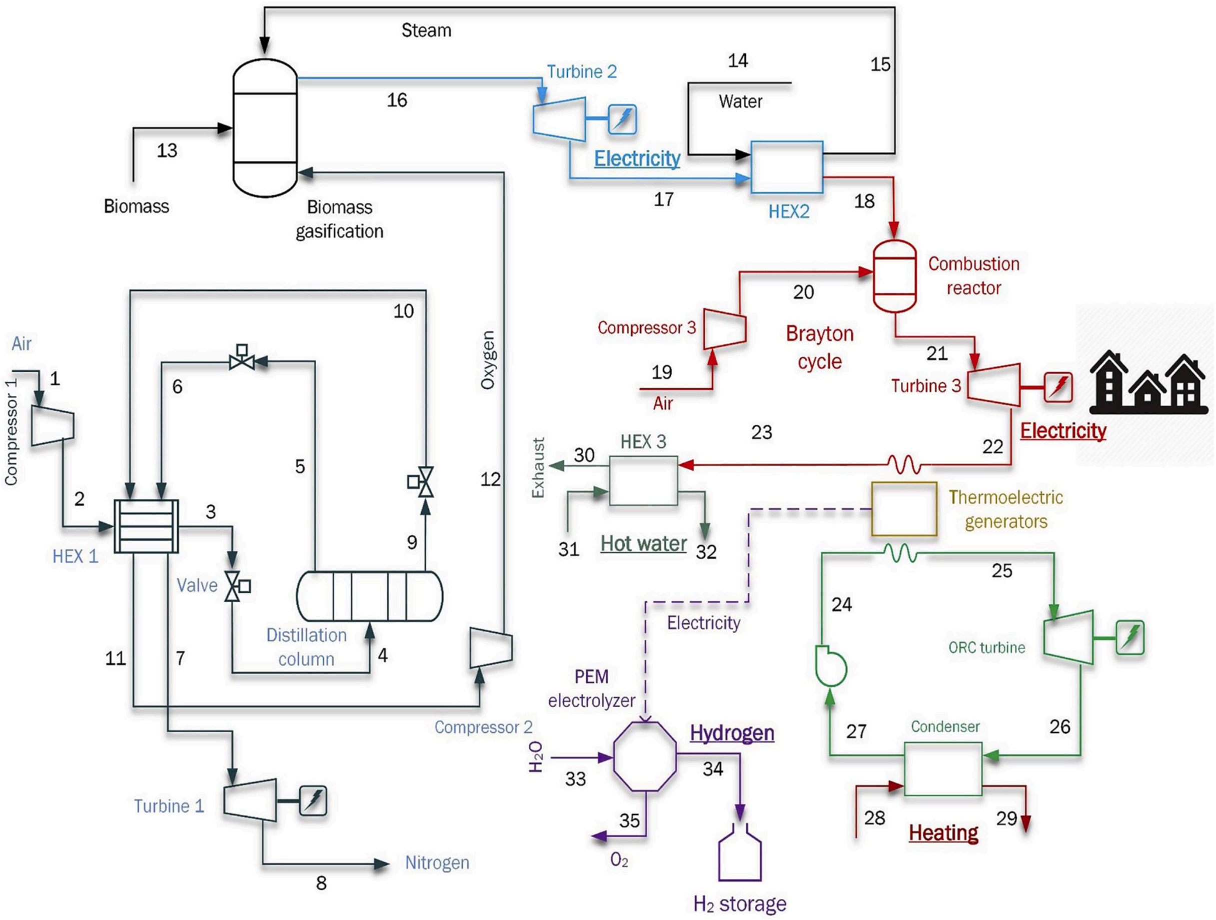


Fig. 9. The layout configuration simulated by Rashidi et al. (adapted from Rashidi and Khorshidi (2018)).

hydrogen is not injected between cycles. Farajollahi et al. (2022) designed a biomass gasification-based system that produces electricity and hydrogen using municipal solid waste. Hydrogen is produced through a proton exchange membrane electrolyzer. According to the obtained results, the total power generation rate and hydrogen production rate are 3.92 MW and 608.8 m^3/h, respectively. Safari and Dincer (2022) proposed and analyzed a cogeneration energy system for power and hydrogen production. In an innovative study, they integrated the vanadium-chloride thermochemical cycle with a renewable and sustainable biomass energy source. In this system, algal biomass is used as biological feed. The advantage of using this biomass is that it has almost no competition with food production, and its cultivation requires less land and water. The introduced system produces 23.42 kg/h of hydrogen. In another study, Ishaq and Dincer (2021b). provided a novel biomass gasification-based system for renewable hydrogen and energy production. The schematic of this cycle is shown in Fig. 8. The required steam for the gasifier of this plant is provided through a multi-effect desalination unit. Hydrogen production in this system before the water gas shift reactor (WGSR) is 129.5 and after that, is 171 mol/s.

In the articles related to biomass gasification, the importance of trigeneration systems is apparent. As mentioned in the preceding section, the main products of this category of systems are power, heating, and cooling. Rashidi and Khorshidi (2018) designed a system that produces heating and electricity using biomass gasification. This system involves a biomass gasification subsystem, an organic Rankine cycle, a desalination unit, and a double effect absorption chiller. A multi-objective optimization has been conducted with the aim of minimizing the total cost rate and maximizing the system's exergy efficiency. The system studied by Ishaq et al. (2020) depicted in Fig. 9, is a biomass-based system designed to produce power, heating, hydrogen, and hot water. The advantage of this is using low-grade waste heat for the thermoelectric generator and organic Rankine cycle. So, it provides a new combination of thermoelectric generators in biomass-based systems. The use of low-grade waste heat in thermoelectric generators increases energy efficiency from 56.97 % to 58.03 % and exergy efficiency from 31.39 % to 32.78 %.

In another article, Ishaq and Dincer (2020) developed a biomass gasification-based trigeneration system for power, heating, and hydrogen production. The system is analyzed from energy and exergy viewpoints, and its configuration was investigated to achieve high energy and exergy efficiency. The Rankine steam cycle is integrated with the proton exchange membrane electrolyzer, so that the electrolyzer can supply the power required for hydrogen production from the Rankine steam cycle. The hydrogen production rate is 10.74 mol/s and the net power of the system is 1.4 MW when the biomass flow rate is 0.4 kg/s. Li et al. (2020) proposed a biomass gasification-based system, which is used to produce heating, power, and cooling. The novelty of their study is to investigate the use of CO_2 as an agent in the gasification process. Given that use of steam as a common agent in studies has disadvantages such as excess energy consumption in water to steam conversion, that research suggests CO_2 utilization. In such case, the CO_2 emission of the plant is reduced, and it is also used in a process itself.

After reviewing the cogeneration and tri-generation systems, the recent articles that proposed multi-generation plants are reviewed. Multi-generation systems designed to produce cooling, heating, power, and hydrogen have also been proposed and investigated. Onder et al. (2020) designed a biomass gasification-based system, which is used for drying in addition to the four mentioned products. This system produces

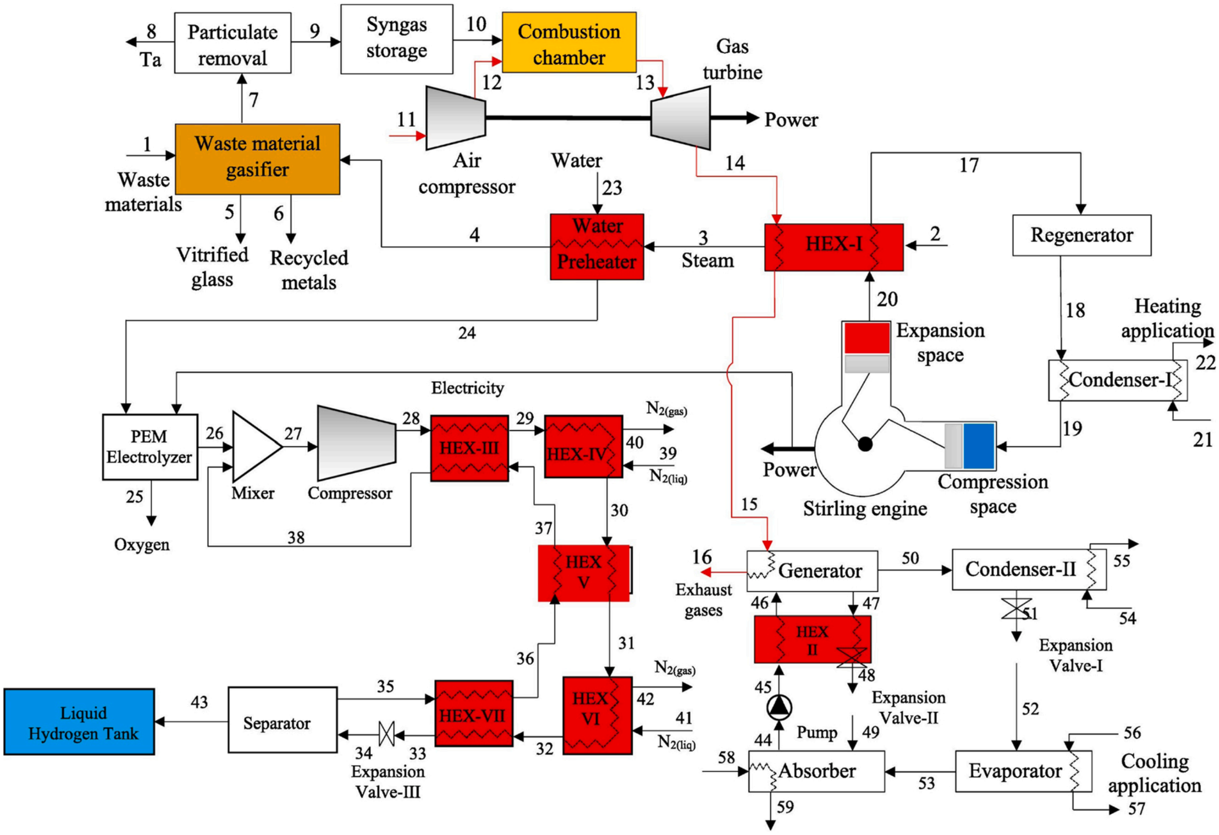


Fig. 10. Schematic of a plant for the production of hydrogen, power, heating, cooling, and hot water (adapted from Yuksel et al. (2019)).

hydrogen using the four-step Cu-Cl thermochemical process. This system consists of eight subsystems, three of which are power generation subsystems, including the Brayton cycle, the Kalina cycle, and the organic Rankine cycle. The results indicate that the power generation rate of each cycle is 18626, 3948, and 1037 kW, respectively. According to the parametric study, the energy efficiency of the system is related to the gasifier temperature with a straight line and shows a linear behavior. Similarly, the results indicate that the total hydrogen production rate is 0.068 kg/s. In another study, Sotoodeh et al. (2022) developed a waste-to-energy polygeneration system that uses biomass gasification to produce power, heating, cooling, and hydrogen. By using thermoelectric generators in the cycle, they have improved 12 % of the electricity production in the cycle. According to the parametric study, the gasification temperature has the greatest impact on the system performance. Hydrogen production rate in the system has been determined to be 0.0718 kg/s. In another article, Yuksel et al. (2019) designed a new polygeneration system to produce hydrogen, power, heating, cooling, and hot water. The mentioned system uses gasification of various waste materials to produce energy and other products. The results indicate that an increase in the gasifier temperature has a desirable impact on increasing the system's exergy efficiency. A schematic of the cycle related to this plant can be seen in Fig. 10.

One of the most popular topics among studies related to biomass gasification-based systems is the integration of freshwater production units with biomass gasification units. Freshwater production is done in different ways, such as reverse osmosis, multi-effect desalination, membrane distillation, and combined membrane and evaporation-based water treatment, etc. Khanmohammadi and Atashkari (2018) have designed a system that generates freshwater, heating, and power using biomass. In this system, freshwater is supplied from multi-effect desalination thermal vapor compression (MED-TVC) unit. The results show that the change of decision variables can change it between 20 % and 42 %, and also, the total cost rate can vary between 100 $ and 600 $/h. According to the results of the parametric study, an increase in the gasifier temperature increases freshwater flow rate and whole system cost. Using biomass energy recovery, Yilmaz et al. (2019) have designed a polygeneration system that provides useful products such as hydrogen, cooling, heating, drying, clean water, and power. Freshwater is obtained through reverse osmosis process, and hydrogen is stored as one of the products of this system by passing through the condensation unit under high pressure. The Kalina cycle is also used instead of the Rankine cycle in this system. In another paper, Yilmaz et al. (2020) evaluated a biomass-based polygeneration system from the thermodynamic standpoint, which uses demolition wood to produce some products such as freshwater, hydrogen, electricity, and heating. Freshwater obtained from this system is achieved from a membrane distillation unit. Similarly, the produced hydrogen is stored in compressed hydrogen form by the compressor unit. Results show that the increase in the temperature reference point and the mass flow rate of biomass increase system efficiency. Hamrang et al. (2020) presented a biomass gasification-based system, a schematic of which is shown in Fig. 11. This plant is integrated to produce electricity and freshwater. Freshwater in this system is provided by the multi-effect desalination unit. Results show that the water production rate and power generated by the system at the optimal point are 11 kg/s and 8.347 MW, respectively. According to a parametric study, an increase in gasification temperature has led to a decrease in power generation.

Safder et al. (2021) have carried out a comprehensive energy, economic, exergy, and exergorisk analyses that have been designed on a polygeneration system to produce freshwater, power, and cooling. The freshwater obtained from this system is achieved from a multi-effect desalination unit. Siddiqui and Dincer (2021) designed a system based on rice husk gasification, which is used to produce power, cooling, heating, and freshwater. Freshwater production in the cycle is done via combined membrane and evaporation-based water treatment. The advantage of this system is that in addition to preventing biological

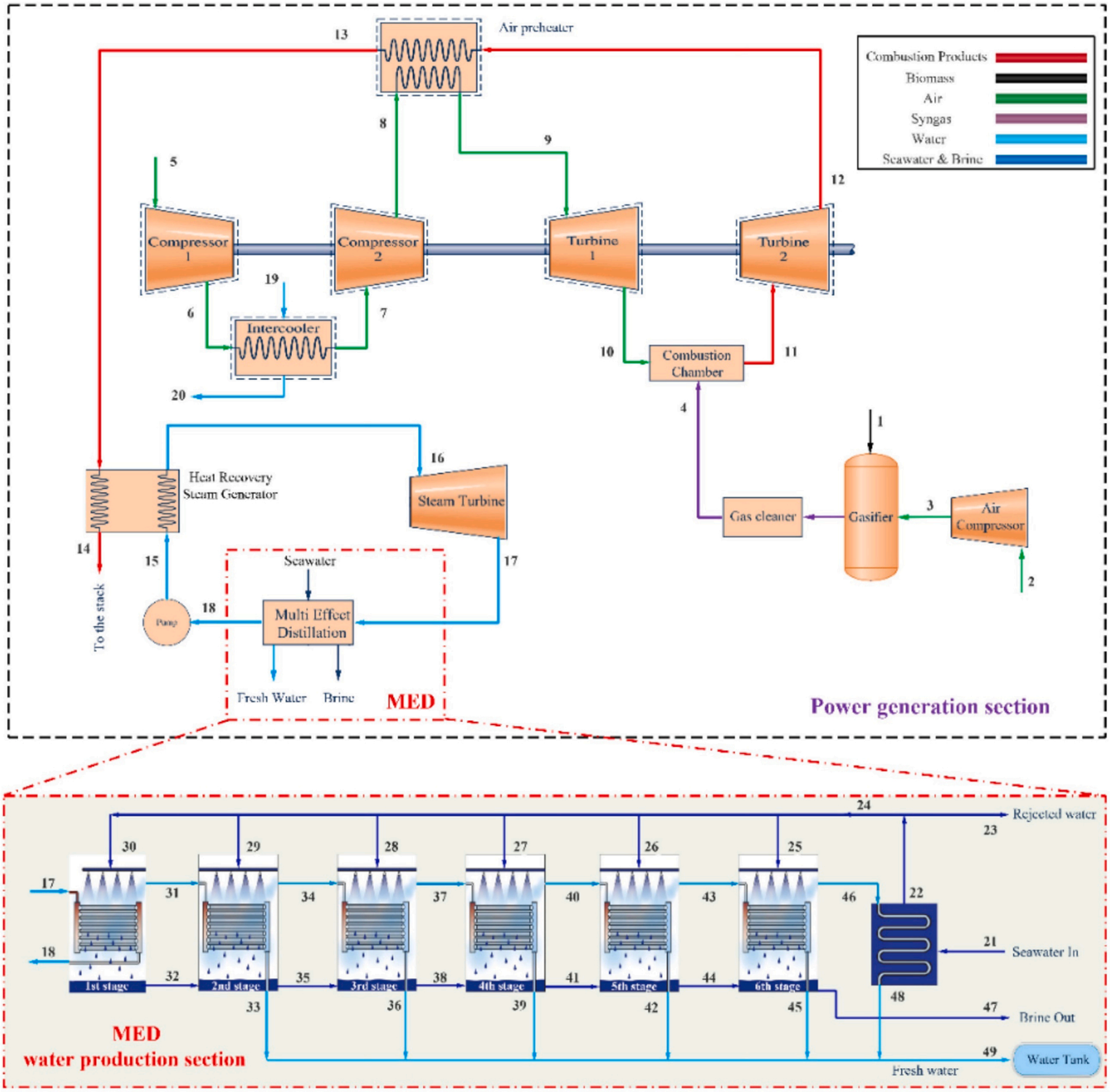


Fig. 11. A biomass gasification-based system for electricity and freshwater production (adapted from Hamrang et al. (2020)).

pollution of rice husk as a waste, it uses this waste to produce energy and other useful products. Results showed that an increase in the biomass rate to 2.2 kg/s increases the energy and exergy efficiencies by 2.8 % and 8.5 %, respectively. Musharavati et al. (2022) presented a biomass-based polygeneration system, which is used to produce electricity and freshwater. Freshwater is supplied through a multi-effect desalination unit with thermal vapor compression, and power is supplied through a gas turbine. The results of the parametric study show that increasing biomass flow rate is beneficial to the system, because it increases the production of both products and reduces costs.

Among recent articles, systems have been presented by researchers that produce chemical products or biofuels. Ishaq and Dincer (2021a) investigated a new ammonia synthesis system that provides energy using biomass gasification. This new configuration takes advantage of the recently developed cascade ammonia synthesis to produce two products: ammonia and electricity. In this system, the ammonia production unit uses pure hydrogen to improve the ammonia conversion efficiency. In addition, the two-stage production of ammonia using Stoichiometric and Gibbs reactors has been investigated. The ammonia production rate and power obtained 21.9 kmol/h and 3405 kW, respectively. Li et al. (2021) designed a biomass gasification-based system, which was used to produce methanol, syngas, light olefin, and raw fuel gas. Various assessments have been done on the gasifier performance as the main element of the biomass conversion system, and the effect of key parameters has been measured on it. The schematic of the cycle presented in this paper is shown in Fig. 12.

Taheri et al. (2021) designed and optimized a polygeneration system that produces power, cooling, natural gas, and hydrogen. This system is fueled using solid waste biomass and provides energy via gasification. Lak Kamari et al. (2021) designed a system based on rice straw gasification, which is used to produce ethanol, biogas, heating, and power. Due to the high rice production rate in Iran and considering that 1.25 tons of rice straw are produced for each ton of rice, the feasibility of using Iranian rice straw in this polygeneration system has been evaluated. The results show that the annual production of electrical energy from this system is 1750 GWh. Table 5 provides a summary of the systems reviewed in this section.

- Fuel cell-based Plants

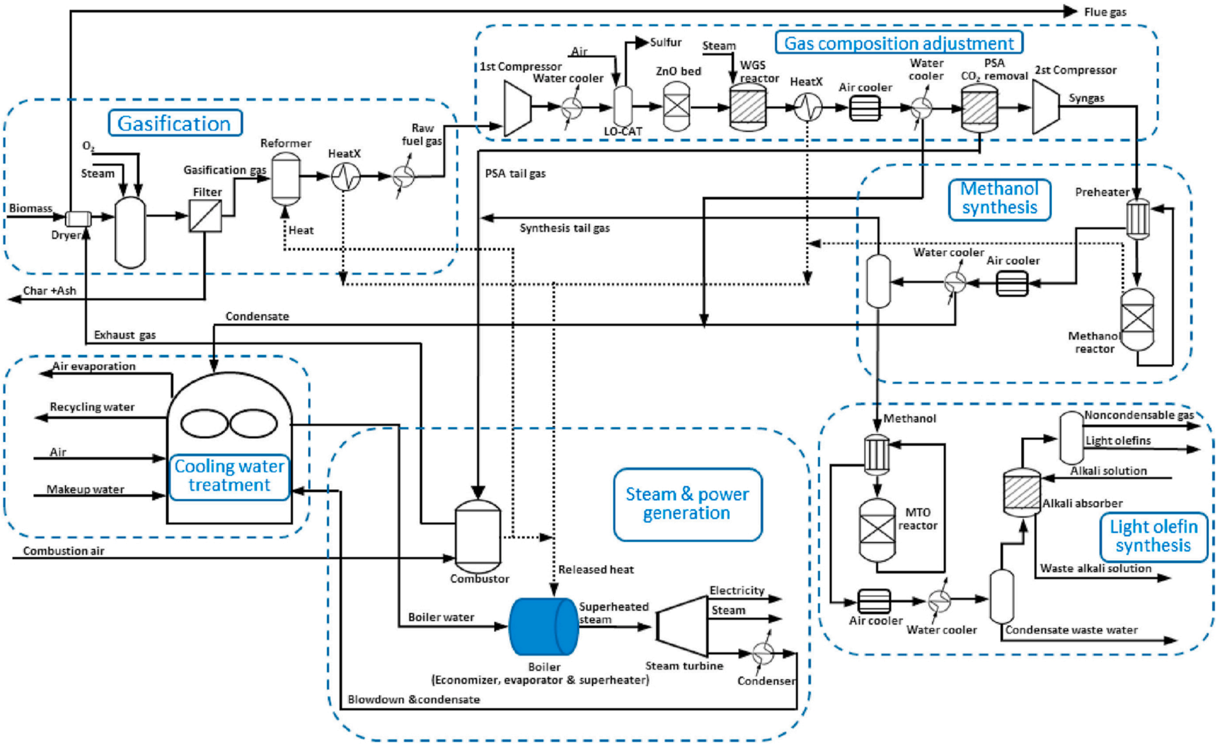


Fig. 12. A plant for methanol, syngas, light olefin, and raw fuel gas production (adapted from Li et al. (2021)).

Due to the importance of fuel cells as one of the novel power generation technologies, biomass gasification-based fuel cell-based systems will be reviewed separately. Fuel cells are the most efficient and low-emission devices that convert the chemical energy of fuel into electrical energy directly. There are different types of fuel cells, and each type has its own advantages and disadvantages; however, solid oxide fuel cells are the most desirable alternative for use in power plants. This class of fuel cells has received high attention due to its advantages such as working in high-temperature conditions, high energy efficiency, and high-power density. Integration of biomass gasification with solid oxide fuel Cell is a promising technology, especially for small scale decentralized power plants (Cao et al., 2022a). Among the recent studies on biomass gasification-based systems integrated with fuel cells, some power plants are single generation, not polygeneration. Many others are polygeneration systems that produce power and other various products by integrating several subsystems with fuel cells. Although the scope of the current article is limited to the investigation of polygeneration systems, due to the special importance of fuel cells, fuel cell-based single generation power plants fed with biomass have also been discussed. Yan et al. (2019) presented a novel biomass fueled power plant with carbon capture and sequestration (BFP-CCS), and it filled the existing studies gaps in this field by designing a novel system to improve electrical efficiency, measuring the levelized cost of the electricity, and carbon dioxide life cycle emission assessment. Roy et al. (2019) designed a power plant that results from the integration of three subsystems, including a solid oxide fuel cell, an externally fired gas turbine, and an organic Rankine cycle. The schematic of the cycle presented by them is shown in Fig. 13. The innovation of their research is integrating the externally fired gas turbine with solid oxide fuel cell.

Salehi et al. (2019) presented a biomass gasification-based plant integrated with molten carbonate fuel cell. This plant incorporates a Stirling engine with an organic Rankine cycle and a fuel cell gasifier to increase the efficiency of the Stirling engine, which is exclusively about 40 % by itself. Owebor et al. (2019) proposed a biomass-based power plant that feeds from Port Harcourt's municipal solid waste and thus converts it into a useful product while preventing waste impacts. The results have shown that the net power produced by the power plant is 219.94 MW. Cheng et al. (2021) focused on the feasibility of a biomass-based power plant that uses solid oxide fuel cell unit, a gas turbine, and an organic flash cycle to power generation. The utilization of the organic flash cycle has been done with the aim of heat recovery of solid oxide fuel cell heat recovery to reduce the environmental impacts and increase electricity production.

After evaluating single generation power plants based on fuel cells, the power plants with two or more products will be mentioned. Sadeghi et al. (2018) designed a system based on municipal solid waste biomass that produces power and heating. The system has been multi-objective optimized in two scenarios. The first scenario, which has an economic aspect, targets the two functions of total exergy and total product cost unit of the system. The second scenario, which has an environmental aspect, targets the other two functions of total exergy and normalized emission. Another biomass gasification-based heat and power plant integrated with a fuel cell was also proposed by Roy et al. (2020b) The results show that the system's energy efficiency at the optimal point is 46.58 %. Karimi et al. (2020) also proposed a system with power and heating products. Considering the enormous amount of rice production in Iran as well as the production of a large amount of rice straw that is obtained as waste, they designed the system based on the gasification of rice straw and conducted a case study to compare the energy obtained from this system and the energy required to collect rice straw. The schematic of the system studied in this article is shown in Fig. 14.

Hydrogen is one of the important products obtained from fuel cell-based systems, especially biomass gasification-based systems. The importance of hydrogen as a green fuel has encouraged researchers to produce this important product using environmentally friendly methods so that the product itself, as well as its production method, should be desirable. Furthermore, freshwater production, especially using novel technologies such as production in polygeneration systems, the integration of water production units with technologies such as fuel cells, etc., has also received the attention of researchers. Yuksel et al. (2020) proposed a biomass-based system producing electricity, freshwater, hydrogen, heating, and cooling. The results showed that the production

Table 5
Summary of studies on biomass gasification-based plants.

Biomass	Devices	Outputs	Conclusion	Ref.
Solid biomass	biomass gasification, an indirectly heated gas turbine cycle and a waste-heated ammonia–water VAR cycle	Power and cooling	maximum electrical power energy efficiency= 27 % at a gas turbine cycle pressure ratio 10 when the gas turbine inlet air temperature is 1100 °C, $\psi = 27.6$ %, maximum Ex_d at gasifier	(Chattopadhyay and Ghosh, 2018)
Wood	SCO_2 cycle, gasifier, combustion chamber, and a domestic water heater	Heating and power	$\eta = 75.89$ %, $\psi = 39.09$%, $\psi_{opt} = 38.42$ %, maximum Ex_d at Combustion chamber, Levelized CO_2 emissions= 0.4757 t/MWh, total product cost= 7.517 $/GJ, 9 % annual greenhouse gas emission reduction after the optimization	(Cao et al., 2021a)
Wood	a gas turbine cycle, a supercritical CO2 cycle, and a Kalina cycle	Heating and power	$\eta = 78.15$ %, $\psi = 40.97$ %, maximum Ex_d at combustion chamber, payback period= 6.9 years, net present value= 5.374×10^6 $ for the electricity price of 0.07 $/kWh and fuel cost of 2 $/GJ	(Ji-chao and Sobhani, 2021)
Wood	gas and steam turbine cycles, hydrogen production cycle and biomass gasification unit	Power and hydrogen	utilizing H_2 injection reduces fuel consumption, η and ψ, exergy loss rate, exergy destruction rate, and CO_2 emission by 27 %, 45 %, 78 %, 11 %, and 32 %, and increases total unit product cost and relative cost difference by 27 %, and 40 %	(Moharamian et al., 2018)
Municipal solid waste	a gas turbine, a gasifier, a transcritical Rankine cycle, and a proton exchange membrane electrolyzer	Power and hydrogen	$\psi = 29.44$ %, maximum Ex_d at gasifier, energy utilization factor= 34.71 %, the overall Ex_d rate= 11,854 kW	(Farajollahi et al., 2022)
Algal biomass	a three-step V-Cl thermochemical cycle, a Brayton power generation cycle and a biomass gasification unit fed by Cladophora glomerata macroalgae as a marine biomass	Green hydrogen and power	$\eta = 53.2$ %, $\psi = 52.6$ %, $\psi_{opt} = 60.45$ %, maximum Ex_d at Combustion chamber, optimum total cost per unit of exergy= 14.46 g_{CO2}/kWh, optimum environmental impacts= 6.36 $/GJ	(Safari and Dincer, 2022)
Corn straw	multi-effect desalination unit, biomass gasification unit, heat recovery steam generation, Brayton cycle, space heating, water gas shift reactor, and hydrogen compression unit	Power and renewable hydrogen	$\eta = 40.86$ %, $\psi = 38.63$ %	(Ishaq and Dincer, 2021b)
N.M	biomass combustor, organic Rankine cycle, domestic water heater, absorption chiller, and reverse osmosis desalination unit	Cooling, heating, and power	total cost rate= 293.8 $/h, CO_2 emission of system= 0.374 kg/kWh,	(Rashidi and Khorshidi, 2018)
Rice husk	gasification, cryogenic air separation unit, Brayton cycle, heat recovery and domestic hot water production	Power, hydrogen, and heating	$\eta = 58.03$ %, $\psi = 32.78$ %, total operating cost= 0.41 $M/year, Net power output= 2.54 MW	(Ishaq et al., 2020)
Dry olive pits	an entrained flow gasifier, a Cryogenic Air Separation unit, a double-stage Rankine cycle, Water Gas Shift Reactor, a combined gas–steam power cycle and a Proton Exchange Membrane electrolyzer	Electricity, heating and hydrogen	$\eta = 53.7$ %, $\psi = 45.5$ %	(Ishaq and Dincer, 2020)
Sawdust	biomass gasification and heat recovery, water gas shift, and CO2 capture	Heating, power, and cooling	during summer: η_{opt}= 53.25 %, $\psi_{opt} = 25.35$ %, during winter: η_{opt}= 50.30 %, $\psi_{opt} = 26.82$ %, maximum Ex_d at gasifier, cost of production= 0.109 $/kWh, payback period= 3.78 years	(Li et al., 2020)
Sawdust wood	biomass gasification, Brayton cycle, Kalina cycle, organic Rankine cycle, cascade refrigeration plant, drying system, hydrogen generation with copper–chlorine thermochemical process, and hydrogen liquefaction process	Electrical energy, hydrogen, heating, cooling, drying, and hot water	$\eta = 56.71$ %, $\psi = 53.59$ %, maximum Ex_d at Bryton cycle (13,583 kW), total irreversibility rate= 47,921 kW	(Onder et al., 2020)
Woody biomass	steam gasifier, organic Rankine, Brayton waste heat recovery, absorption refrigeration systems, hydrogen production, and domestic heating systems	Power, heating, cooling, and hydrogen	$\eta = 52.3$ %, $\psi = 41.3$ %, maximum Ex_d at gasifier, the power generation showed an improvement of 12 % by the modification of this plant	(Sotoodeh et al., 2022)
Various waste materials	waste material gasification, Brayton cycle, Stirling engine cycle, single effect absorption cooling system, and hydrogen production and liquefaction cycle	Hydrogen, power, heating-cooling, and hot water	$\eta = 61.57$ %, $\psi = 58.15$ %, maximum Ex_d at gasifier, best compressor pressure ratio for the maximum energetic and exergetic performances and also hydrogen production= 4	(Yuksel et al., 2019)
N.M.	a biomass gasifier, a combustion chamber, heat recovery steam generator, multi-effect desalination thermal vapor compression	Freshwater, electricity, and hot water	$\psi = 27.9$ %, maximum Ex_d at gasifier	(Khanmohammadi and Atashkari, 2018)
Demolition wood	biomass gasifier unit, gas turbine cycle, Kalina cycle, reverse osmosis unit, proton exchange membrane electrolyzer, absorption cooling cycle, dryer and heat pump	Cooling, hydrogen, heating, drying, hot water, and power	$\eta = 63.84$ %, $\psi = 59.26$ %, maximum Ex_d at gasifier, total irreversibility= 53,406 kW, overall purchase cost rate= 2000 $/s	(Yilmaz et al., 2019)
Demolition wood	a biomass gasifier cycle, clean water production system, hydrogen production, hydrogen compression, gas turbine sub-plant, and Rankine cycle	Hydrogen, electricity, heating, and clean water	$\eta = 52.84$ %, $\psi = 46.59$ %, maximum Ex_d at gasifier (12,685 kW), total irreversibility= 37,743 kW	(Yilmaz et al., 2020)
N.M.	gasification and gas turbine cycle as the main system, and a steam Rankine cycle and multi-effect desalination system as the waste heat recovery units	Electricity and freshwater	$\psi = 46.22$ %, maximum Ex_d at combustion chamber (3250 kW), Sum unit cost of product= 14.07 $/GJ, total net present value at the end of plant's lifespan= 6.547×10^6 $, payback period= 6.75 years	(Hamrang et al., 2020)

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Table 5 (*continued*)

Biomass	Devices	Outputs	Conclusion	Ref.
Sugarcane bagasse	a bagasse-biomass based gasifier-Brayton cycle, a Rankine cycle, a Kalina cycle, an ejector refrigeration cycle, and a multi-effect desalination unit	Power, freshwater, and cooling	$\eta_{opt} = 92.10$ %, $\psi_{opt} = 77.49$ %, maximum Ex_d at turbine, optimum total accidental risk impact = 92.59 %	(Safder et al., 2021)
Rice husk	Biomass gasification, Brayton cycle, Absorption cooling cycle, Brine wastewater treatment system, Thermoelectric generator, Organic Rankine cycle	Electricity, cooling, heating, and freshwater	$\eta = 66.4$ %, $\psi = 44.4$ %, maximum Ex_d at turbine (26.1 MW)	(Siddiqui and Dincer, 2021)
Wood	a gasifier, a compressor, a heat exchanger, a gas turbine, a combustion chamber, and a multi-effect desalination with thermal vapor compression	Power and desalinated water	$\psi_{opt} = 15.61$ %, maximum Ex_d at gasifier, optimum total cost rate= 206.78 $/h, only 12 % of the biomass chemical exergy is converted to electricity, while 82 % is destroyed	(Musharavati et al., 2022)
Corn straw	biomass gasifier, heat recovery unit for syngas cooling, combined cycle, water gas shift reactor system, pressure swing adsorption and ammonia production unit	Ammonia and electrical power	$\eta = 42.4$ %, $\psi = 44.2$ %	(Ishaq and Dincer, 2021a)
Poplar	gasification, gas composition adjustment, methanol synthesis, light olefin synthesis, steam & power generation and cooling water treatment	raw fuel gas, syngas, methanol, and light olefins	$\psi = 30.5$ %, maximum Ex_d at gasifier, usage of power= 4.22MWh/tonne light olefins, usage of water= 16 tonne/tonne light olefins, mass yield of light olefin= 0.127 tonne/tonne biomass	(Li et al., 2021)
Solid waste	combined gas-steam cycle, a cascade Rankine cycles, a lithium bromide-water absorption refrigeration cycle, a proton exchange membrane electrolyzer, and a liquid natural gas	Power, cooling, natural gas, and hydrogen	$\eta_{opt} = 45.24$ %, $\psi_{opt} = 39.023$ %, maximum Ex_d at gasifier (51,286 kW), optimum total cost rate= 1107 $/h	(Taheri et al., 2021)
Rice straw	a biomass combustor, a Rankine power cycle, a biofuel production plant, a district heating system	Power, Bioethanol, and biogas, heat	$\eta = 63.0$ %, reduction potential of CO_2 emission= 181 kt/year	(Lak Kamari et al., 2021)

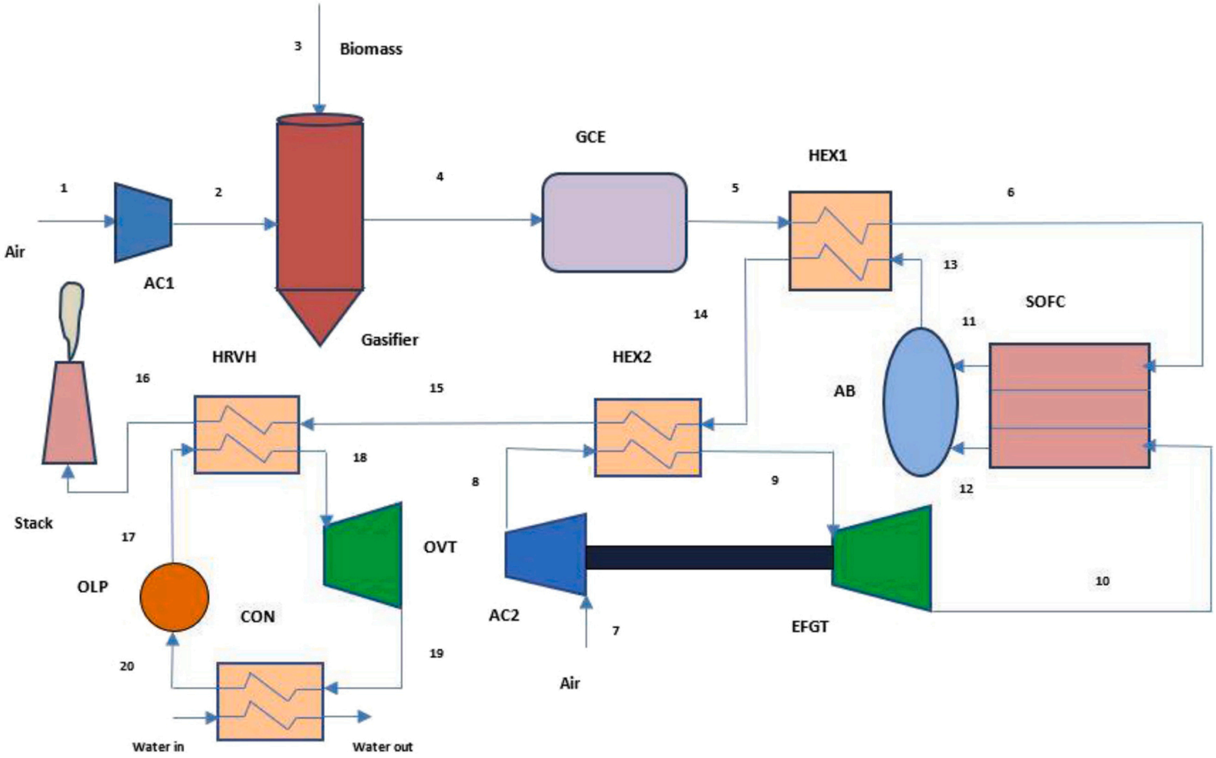

Fig. 13. A fuel cell-based power plant presented by Roy et al. (adapted from Roy et al. (2019)).

of hydrogen and freshwater are 0.028 and 4.86 kg/s, respectively. The parametric study showed that an increase in the gasifier temperature has a positive impact on the entire system and subsystems, and an increase in the reference temperature and the biomass flow rate, increase hydrogen production. Behzadi et al. (2019) integrated a biomass-based fuel cell with other subsystems to obtain electricity, cooling, and freshwater products. Investigations have shown that in the conditions where the plant produces electricity, cooling, and freshwater, will have 19.6 % more exergy efficiency than the plant products are electricity and freshwater. Similarly, it has 26.54 % less environmental impacts. The schematic of the cycle being assessed is shown in Fig. 15.

Ebrahimi et al. (2021) designed an integrated structure consisting of a solid oxide fuel cell, a Stirling engine, a biomass gasification sub-system, and a multi-effect desalination unit, which is used to produce electricity, hot water, and freshwater. The results showed that the moisture content of the input fuel has a significant impact on the system

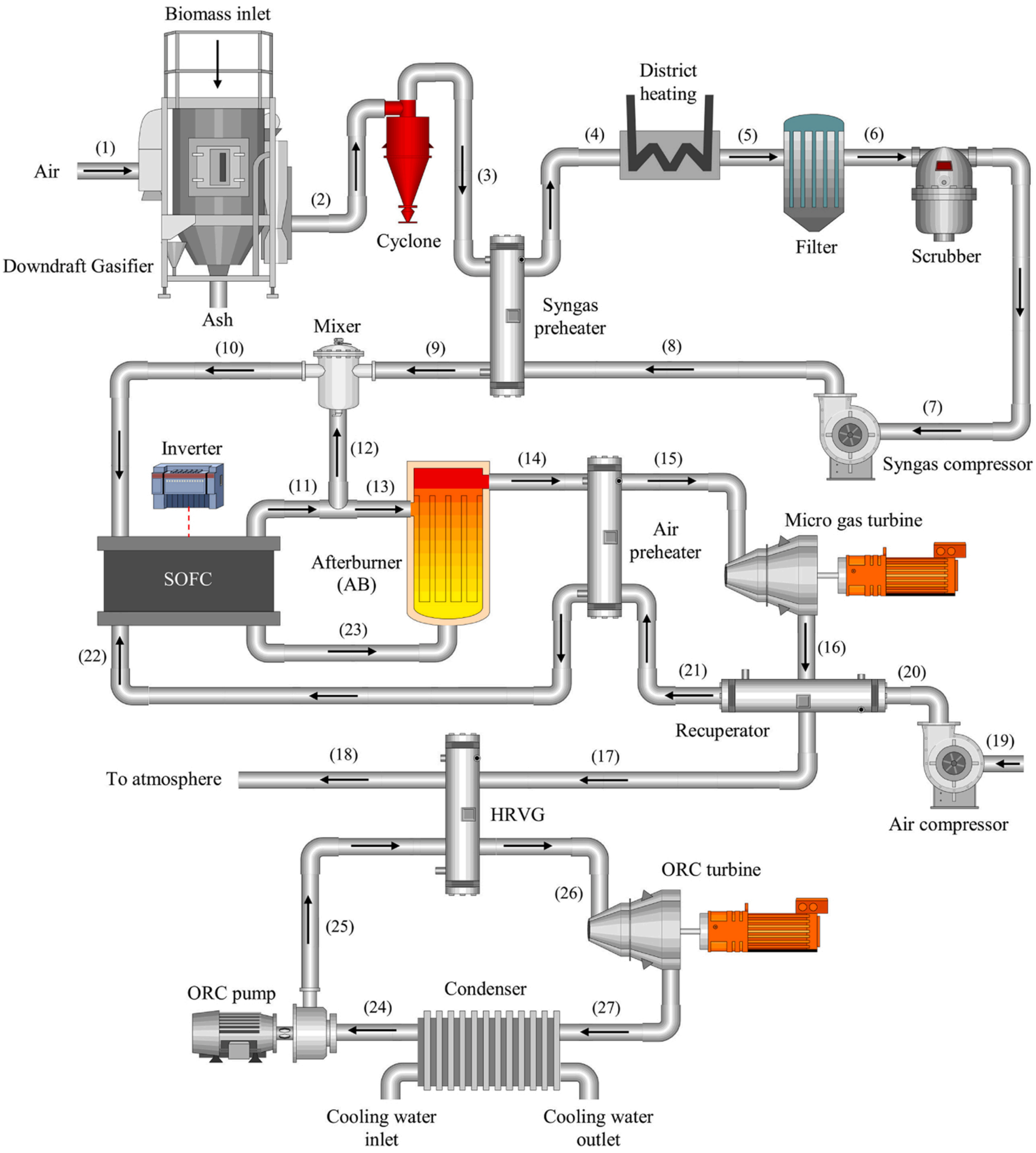

Fig. 14. A plant with gasifier, solid oxide fuel cell, organic Rankine cycle, and gas turbine (adapted from Karimi et al. (2020)).

overall performance. Chen et al. (2021) presented a wood gasification-based system, which is used to produce electricity and freshwater. In this system, freshwater is produced in the humidification-dehumidification (HDH) desalination unit. In another study of biomass-based systems that used fuel cells in their configuration, Ebrahimi et al. (2021) designed a system that uses agricultural waste to produce electricity, cold energy, gasification by-products, and hot water. The results have shown that the payback time for this system is 1.77 years; also, the total fuel efficiency can reach 59.35 %. A summary of the articles mentioned in this section is presented in Table 6.

3.1.2.2. Comparative studies. Due to the importance of biomass-based systems, researchers conducted some comparative studies to compare the impact of different scenarios and factors on biomass-based systems. The comparative studies included comparing the configuration of systems to achieve high performance, comparing the use of suitable working fluids for Rankine cycles, comparing the effect of using different agents on the gasifier and system's performance, and comparing the use of different biomasses as system feedstock.

- Configuration comparison

Studies conducted to compare different configurations for systems have attracted a lot of attention in recent years. Habibollahzade et al. (2018) evaluated three systems. In the first system, a solid oxide fuel cell is integrated with a gasifier. The second system uses the waste heat of the first system in the Stirling engine, and the third system employs the excess power of the Stirling engine to produce hydrogen. The lowest total cost of the product is related to the second system. Gholamian et al. (2018) investigated three system configurations. As seen in the schematic depicted in Fig. 16, the first system is a solid oxide fuel cell based on biomass gasification, in which waste heat in the second system is used in a gas turbine to produce power, then the excess power of the gas turbine is used in the third system to produce hydrogen. Results show

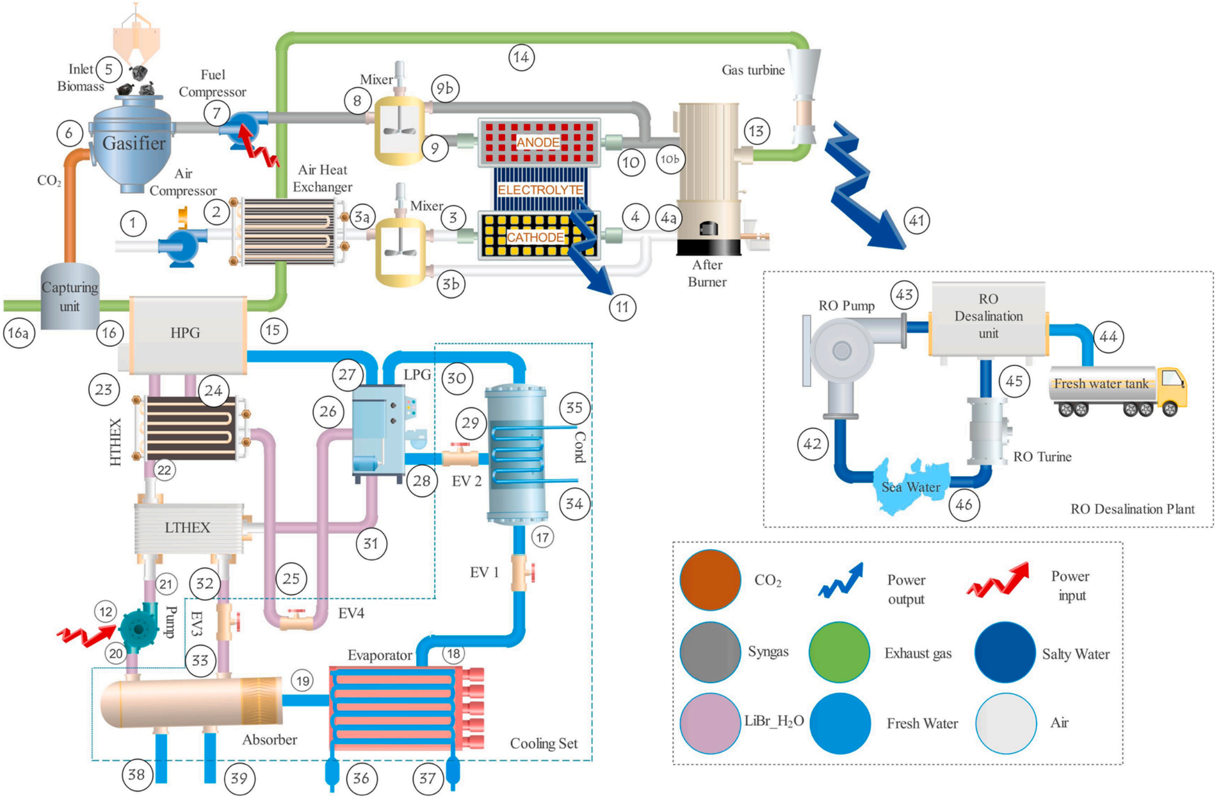

Fig. 15. A biomass driven fuel cell-based plant simulated by Behzadi et al. (adapted from (Behzadi et al. (2019)).

that the second system is the most desirable system, because it has the highest exergy efficiency and the lowest total product cost compared to other systems.

Mehrabadi and Boyaghchi (2019) investigated four different scenarios in a comparative study to configure a biomass-based polygeneration system. In all the scenarios, three products are produced in the same way; although the production of freshwater is different in each one. These four scenarios are respectively: brine recirculation multi-stage flash (BR-MSF), forward feed scheme of multi-stage desalination (FF-MED), backward feed scheme of multi-stage desalination (BF-MED), parallel feed scheme of multi-stage desalination (PF-MED). Houshfar (2020) has compared a conventional waste-to-energy plant (model a) with a waste-to-energy plant in which a thermoelectric generator substitutes its condenser (model b). The findings have indicated that model (b) can be a more desirable alternative for boosting exergetic efficiency and reducing pollution of waste-to-energy plants. Zare (2020) have compared open and closed cycle gas turbine processes with two different modeling approaches. Two approaches were considered as (a): when a proper value is assumed for cold end temperature difference of intermediate heat exchanger, and (b): when a proper value is assumed for heat exchanger effectiveness. Approach (b) in this study is reported as the appropriate approach due to the rationality of its results. Cao et al. (2021b) have conducted a comparative study to choose the appropriate feeding cycle for exhaust gases from gas turbine. They introduced a biomass fueled eternally fired gas turbine with closed cycle and utilized the exhaust heat in two different cycles. Once, for power generation in an organic Rankine cycle and another for inlet cooling gas compressor via absorption cooling cycle. The results have shown that the second cycle is more rational at the best operating point due to having 11.2 % higher exergy efficiency and 12.3 % lower cost than the first state. Rahimi et al. (2021) have studied a polygeneration system that uses the sugarcane bagasse to generate heating, freshwater, and power. This study has been conducted in the southern regions of Iran by using real data. They have focused on finding the optimal configuration and using heat integration and have done a comparative study for three different cases: (a) without thermal integration, (b) partial thermal integration, and (c) partial and full thermal integration. Habibollahzade et al. (2021b). compared four configurations; in the first system, a biomass-based solid oxide fuel cell is integrated with a double-effect absorption chiller; in the second system, a thermoelectric generator is used instead of a condenser chiller to increase efficiency, and the third system uses the excess power of the second system for hydrogen production, finally, in the fourth system, using CO_2 and hydrogen from the previous systems, methane fuel is produced in a fuel synthesis unit. The second system is the most desirable alternative from exergy efficiency (62.8 %) and total product cost (19.8 \$/GJ) viewpoints. Also, the fourth system has the lowest exergy efficiency (54.4 %) and the highest product cost (21.7 \$/GJ); however, it has the lowest carbon dioxide emission (0.29 t/MWh), which is related to the same system. Cao et al. (2022b) designed a polygeneration system based on a molten carbonate fuel cell. Hydrogen production in this system has been compared using two different scenarios, first by a proton exchange membrane electrolyzer and the other via the vanadium chloride (VCL) cycle. Investigations have shown that the integration of the vanadium chloride cycle with the mentioned system has performed better than proton exchange membrane electrolyzer. The characteristics of the mentioned articles are presented in Table 7.

- Working fluid comparison

In addition to comparative studies to determine the optimal configuration, studies have also been conducted to compare suitable working fluids for organic cycles in biomass-based systems. Boyaghchi et al. (2018) considered a paper biomass gasification-based system to produce syngas, power, heating, hydrogen, oxygen, and refrigeration effect. This system has been compared using three groups of organic working fluids: R600-R290, R236fa-R1234yf, and R245fa-R134a. Behzadi et al. (2018a) studied a waste-to-energy power plant coupled with an organic Rankine

Table 6
Summary of studies on biomass driven fuel cell-based plants.

Biomass	Devices	Outputs	Conclusion	Ref.
Solid biomass	chemical looping air separation unit, fluidized bed gasifier, solid oxide fuel cell, post combustion chamber, heat recovery and steam generator, steam turbine	Power	Electrical power energy efficiency= 51.7 %, maximum Ex_d at solid oxide fuel cell, life cycle CO_2 emission= 0.0501 \$ /kWh, levelized cost of electricity= −0.591 kg/kWh	(Yan et al., 2019)
Woody biomass	a biomass gasification-based power plant integrating a solid oxide fuel cell module, an externally fired gas turbine, and an organic Rankine cycle	Power	$\eta = 49.47$ %, $\psi = 44.2$ %, maximum Ex_d at gasifier, minimum levelized unit cost of electricity= 0.086 \$/kWh, maximum CO_2 emission reduction potential= 3564 t CO_2/year, maximum environmental benefit from the present system= 51,671 \$/year	(Roy et al., 2019)
Paper	a biomass gasifier, a molten carbonate fuel cell, a heat recovery steam generator unit, a Stirling engine, and an organic Rankine cycle	Power	$\psi = 50.18$ %, maximum Ex_d at gasifier (58.01 kW), total exergy destruction rate= 224.19 kW,CO_2 emission= 28.9×10^{-2} t.MWh^{-1}	(Salehi et al., 2019)
Municipal waste	gasification, solid oxide fuel cell, gas turbine, steam turbine, organic Rankine cycle, and absorption refrigeration cycles	Power	$\eta = 62.3$ %, $\psi = 55.5$ %, maximum Ex_d at combustion chamber, unit cost of energy= 0.018 \$/kWh, life cycle cost= \$227.8 million, fuel harmful emission factor= 0.0009, specific CO_2 emission= 148.22 $kgCO_2$/MWh, sustainability exponent= 6.57, energy content of the syngas produced from the gasification process= 5366 kJ/kg	(Owebor et al., 2019)
N.M.	biomass-based solid oxide fuel cell, and gas turbine system combined with the organic flash cycle	Power	$\eta = 49.37$ %, $\psi = 42.50$ %, maximum Ex_d at air heat exchanger, total net present value at the end of plant lifetime= 9.8×10^5 \$, payback period= 4.25 years, $\psi_{opt} = 47.12$ %, optimum levelized total emission= 23.24 t/MWh, Cost per exergy unit= 5.50 \$/GJ	(Cheng et al., 2021)
Municipal solid waste	gasifier, solid oxide fuel cell Stack, heat recovery steam generator, after burner, air blower, air Pre-heater, pump, mixer, cyclone	Heating and power	maximum Ex_d at gasifier, maximum $\psi = 38.7$ %, minimum unit product cost= 33.99 \$/GJ	(Sadeghi et al., 2018)
Rice straw	a downdraft gasifier, a solid oxide fuel cell, a micro gas turbine, and an organic Rankine cycle	Power and heating	$\psi_{opt} = 35.1$ %, maximum Ex_d at combustion chamber, optimum cost rate= 10.2 \$/h	(Karimi et al., 2020)
Sawdust	biomass gasifier, a solid oxide fuel cell module, and a heat recovery steam generator	Power and process heat	$\psi_{opt} = 46.58$ %, optimum levelized cost of energy= 0.0454 \$/kWh, optimum levelized cost of exergy= 0.0657\$/kWh	(Roy et al., 2020b)
Olive pits	Solid oxide fuel cell, distillation process, Rankine cycle, ORC with an ejector refrigeration process, and hydrogen production, and compression	Electricity, hydrogen, fresh and hot water, heating, and cooling	$\eta = 56.17$ %, $\psi = 52.83$ %, maximum Ex_d at biomass gasification supplant	(Yuksel et al., 2020)
Municipal solid waste	a biomass-based solid oxide fuel cell integrated with a gas turbine, a reverse osmosis desalination unit, and double-effect absorption chiller	Power, cooling, and freshwater production	$\psi = 27.07$ %, total product unit cost= 66.46 \$/GJ, environmental impact= 0.2837 t/(MWh), $\psi_{opt} = 38.16$ %, maximum Ex_d at gasifier (179.8 kW), optimum total product unit cost= 69.47 \$/GJ	(Behzadi et al., 2019)
Wood	a solid oxide fuel cell, a Stirling engine, an organic Rankine cycle, and a multi-effect distillation	Power, desalinated water, hot water	Electrical power energy efficiency= 62.88 %, $\psi = 51.56$ %, maximum Ex_d at solid oxide fuel cell, total exergy destruction rate= 5666 kW	(Ebrahimi et al., 2021)
Wood	biomass gasification, SOFC with anode and cathode recycling, gas turbine, Kalina cycle, and humidification dehumidification desalination system	Electricity and freshwater	$\eta = 47.49$ %, $\psi = 36.14$ %, total unit exergy cost= 6.48 \$/GJ, $\psi_{opt} = 49.455$ %, maximum Ex_d at heat exchanger, optimum total unit exergy cost= 4.912 \$/GJ	(Chen et al., 2021)
Rice straw	biomass gasifier, solid oxide fuel cell, homogeneous charge compression ignition engine, regenerative S-CO_2 cycle and ammonia-water ARC	electricity, cold energy, hot water and gasification byproducts	maximum Ex_d at gasifier, total fuel efficiency= 59.35 %, payback time= 1.77 years	(Zhao et al., 2022)

cycle. They investigated several different working fluids, including R123, normal heptane, R11, R141-b, Isohexane, and R717, in setting up the organic Rankine cycle. Fakhari et al. (2021) proposed a fuel cell-based polygeneration system based on biomass gasification, which is used for power, heating, and freshwater production. Zeotropic mixtures used in this study are: R113-R114, R134a-R245fa, R610a-C2Butene, R610-Hexene, and R600-R610. The studies mentioned in this section that compare the working fluids used in the organic Rankine cycles of biomass-based systems are summarized in Table 8.

- Agent comparison

As mentioned in the previous sections, the agent is one of the most effective factors in biomass gasification. In this regard, comparative studies have been conducted to investigate the impact of the agent on the gasifier performance and biomass gasification based-systems. Shayan et al. (2018) have conducted a comparative study to evaluate the effect of different factors in the biomass gasification process. They have chosen four different agents, including air, air-enriched with oxygen, oxygen, and steam, as well as two biomasses; paper and wood. The results show that increasing the gasification temperature regardless of the type of the agent causes a decrease in hydrogen production and the heating value of the syngas. Hosseinpour et al. (2020) introduced a system based on gasification of municipal solid waste integrated with a solid oxide fuel cell. They studied the effect of using four different agents, including air, air-enriched with oxygen, oxygen, and steam, on the system. Behzadi et al. (2020) proposed municipal solid waste gasification-based system that produces power through a proton exchange membrane fuel cell to produce power, heat, and hot water. They measured the impact of using two different agents, including steam and air, on the important properties of the system. Habibollahzade et al. (2021a) investigated biomass gasification in different mediums, including air, oxygen, air-enriched with oxygen, steam, carbon dioxide, and a mixture of these. Investigations have been conducted comprehensively, and the results have been reported and analyzed in detail. Safarian et al. (2022) have conducted a study to compare two air and air-steam mixture agents on a combined cycle. Timber and wood waste are considered as the feed of the system. The results of this study showed that when the air-steam mixture is used as an agent, the amount of hydrogen production is higher than when air is used, regardless of the system temperature. The syngas obtained from gasification is more in the temperature range of 500–700 °C in air and steam-based system;

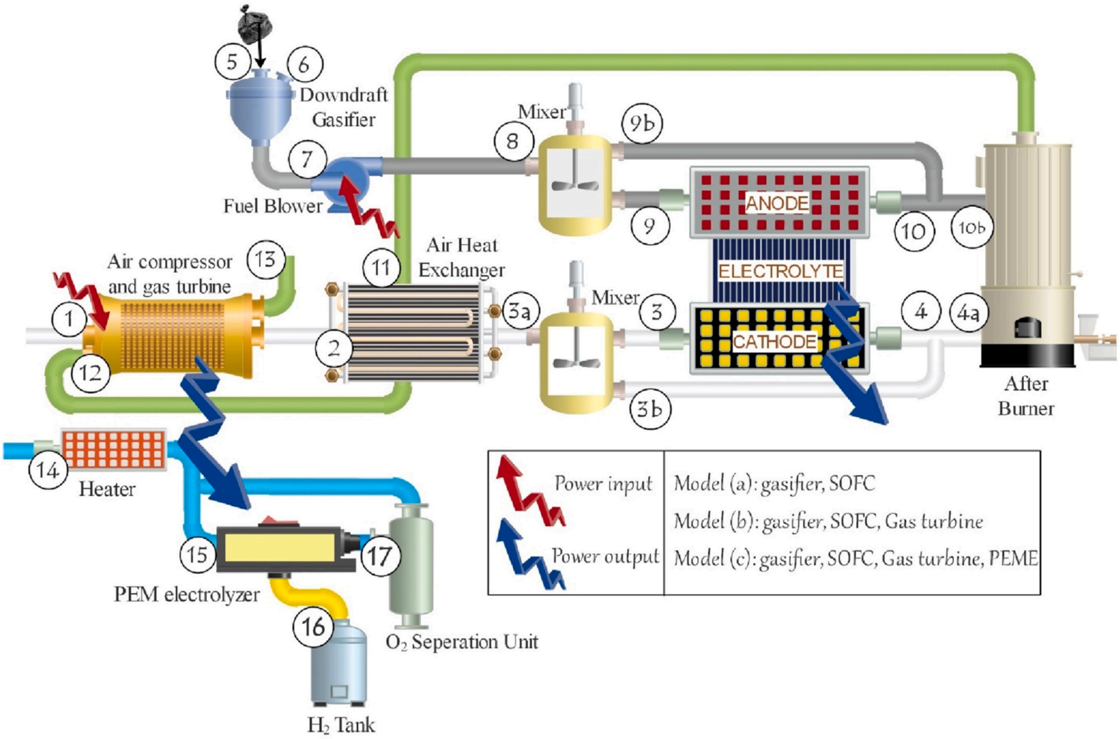

Fig. 16. The configuration proposed by Gholamian et al. (adapted from Gholamian et al. (2018)).

however, with an increase in temperature, the situation is reversed, and this parameter increases in air-based system. Table 9 provides a summary of this category of articles that were discussed.

- Biomass comparison

Finally, studies will be addressed that have compared the use of different types of biomasses and their effect on the behavior and efficiency of systems. Ghaffarpour et al. (2018) presented a power plant based on a biomass-based fuel cell and investigated the performance of the system by considering three different biomasses, Pine sawdust, municipal solid waste, and fowl manure. The results have shown that when using pine sawdust biomass, the energy and exergy efficiency are the highest, and unit production cost, and the total system cost rate is the lowest compared to other biomasses, but it is not favorable from an environmental viewpoint and has the most carbon dioxide content. Also, for using the fowl manure, the net electric power generated by the system is the highest, and the carbon dioxide emission is the lowest among other biomasses. Roy (2020) designed a biomass-based power plant and investigated three different types of biomasses, including paper, wood, and rice husk. Multi-criteria decision-making technique shows that rice husk has the best performance compared to other investigated feeds. Mojaver et al. (2020) designed a power plant and investigated the effect of using sunflower shell, rice husk, pine sawdust, etc., as the feed of system. The behavior of the system was analyzed from energy, exergy, and environmental viewpoints. According to the results of multi-criteria decision making, in selecting the best biomass, which was considered with different criteria such as system exergy destruction rate, carbon dioxide emission, energy efficiency, etc., eucalyptus biomass was introduced as the best alternative. Roy et al. (2020a) investigated seven different types of biomasses for use in a power plant includes: bagasse, sawdust, pine bark, straw, cotton stalk, wood, and torrefied pellet. Environmental studies also indicate that the mentioned system can reduce up to 1510 tons of CO_2/year. Teng et al. (2021) proposed a novel biomass gasification-based power plant and studied the impact of using six different types of biomasses. Mehrabadi and Boyaghchi (2021) have also developed a system of electricity and freshwater production that supplies freshwater from a multi-stage flash desalination with a brine recirculation unit. Four different types of biomasses, including municipal solid waste, wood, paper, and sawdust, have been selected and evaluated as feed in this system. The maximum amount of freshwater production and power in this system belongs to using wood and sawdust biomass, respectively, and the municipal solid waste biomass has the lowest level of carbon dioxide emissions compared to the rest biomass. Cao and Ehyaei (2021) presented a biomass-based cogeneration system designed for power and cooling generation. This study has used the steam turbine and steam generator in the cycle to increase the power generation. In this article, the results obtained for other types of biomasses have also been measured, and the effect of feed change has been investigated. Xu et al. (2022) designed a system that uses biomass to produce three products: electricity, hydrogen, and freshwater. In this system, freshwater is supplied via the multi-effect desalination process, which is one of the most important methods for energy and environment efficiency enhancement. Also, hydrogen, which is a clean fuel, is produced using a renewable energy source. The biomass used in the baseline design is municipal solid waste; however, the effect of utilizing other biomasses, including paddy husk, paper, and wood, has also been investigated. The parametric study conducted on the system has shown that an increase in the biomass rate increases the production rate of all three products and reduces the total energy cost of the products; however, it causes an increase in the exergy destruction rate and a decrease in exergy efficiency instead. Zaman and Ghosh (2022) proposed a carbon-negative power plant that is fueled with biomass. The configuration of this plant and its integration is novel and has not been investigated in previous articles. The impact of using different biomasses is investigated on the system performance. A summary of the articles that have conducted a comparative study in this field is presented in Table 10.

3.1.3. *Simultaneous use of digestion and gasification*

As mentioned previously, gasification and anaerobic digestion are the most widely used biomass conversion methods that have been

Table 7
Summary of conducted studies on different configurations comparing.

Biomass	Devices	Outputs	Conclusion	Ref.
Municipal solid waste	a) a gasifier with a solid oxide fuel cell, b) waste heat of the first model is reused in the Stirling engine, c) reuse of the surplus power of the Stirling engine in a proton exchange membrane electrolyzer	Power and hydrogen	$\psi_{opt,a} = 28.51$ %, $\psi_{opt,b} = 39.41$ %, $\psi_{opt,c} = 38.03$ %, $\eta_{opt,a}= 31.13$ %, $\eta_{opt,b}= 67.38$ %, $\eta_{opt,c}= 66.41$ %, optimum emission rate of the models (a), (b), and (c)= 19.33 \$/GJ, 18.91 \$/GJ, and 24.93 \$/GJ	(Habibollahzade et al., 2018)
Municipal solid waste	a) a biomass-based solid oxide fuel cell, b) waste heat of the first model is reused in the gas turbine, c) reuse of the surplus power of the gas turbine in a proton exchange membrane electrolyzer	Power and hydrogen	$\psi_{opt,b} = 33.22$ %, $\psi_{opt,c} = 32.3$ %, optimum total product cost of the models (b), and (c)= 19.01 \$/GJ, 20.1 \$/GJ	(Gholamian et al., 2018)
Wood residual	supercritical CO_2 (S-CO_2) Brayton cycle, a biomass gasifier, a milk pasteurization unit, and a: a) brine recirculation multi-stage flash, b) forward feed scheme of multi-effect distillation, c) backward feed scheme of multi-effect distillation, and d) parallel feed scheme of multi-effect distillation	Power, pasteurized milk, biofuel, potable water	model (a) gives the maximum distillate water, the maximum exergy efficiency is obtained for model (b), model (c) gives the lowest total cost and environmental impact (EI) rates, with the values of 400.6 m^3/day, 44.16 %, 77.15 \$/h, and 33.35 mPts/s	(Mehrabadi and Boyaghchi, 2019)
Municipal solid waste	a) Conventional waste-to-energy plant, b) waste-to-energy-thermoelectric generator integrated system	Power	$\psi_{opt,b} = 17.22$ %, optimum total cost rate= 184.2 \$/h, maximum Ex_d at gasifier model (b) has higher power output, higher exergetic efficiency, lower total product cost, and lower CO_2 emission	(Houshfar, 2020)
Wood	a) a biomass-fueled externally fired closed cycle gas turbine, b) conventional open cycle gas turbine	Power	$\psi_a = 23.78$ %, $\psi_b = 20.96$ %, levelized cost of electricity= 65.26 \$/MWh and 77.93 \$/MWh for model (a) and model (b), the model (a) generates more output power by 13.5 %	(Zare, 2020)
Wood	biomass fueled externally fired gas turbine with closed cycle integrated with an a) organic Rankine cycle, or b) inlet cooling of gas compressor via an absorption cooling cycle	Power and refrigeration	the model (b) has 11.2 % higher exergy efficiency and 12.3 % lower electricity cost than the model (a) at multi-objective optimal points, optimum levelized cost of electricity= 56.053\$/MWh and 63.900\$/MWh for model (a) and model (b)	(Cao et al., 2021b)
Sugarcane bagasse	a CHP system with the use of biomass gasification in 3 conditions: a) no heat integration, b) partial heat integration, c) full heat integration	Heat, freshwater, and electricity	total utility consumption= 3113.69 kW and 590.93 kW for no heat integration and partial heat integration, removing one of the heaters and so increasing the integration is possible by increasing the gasification temperature	(Rahimi et al., 2021)
Municipal solid waste, Wood, Paper, Sawdust	a syngas-fuelled solid oxide fuel cell, double-effect absorption chiller (a), a thermoelectric generator unit (b), solid oxide electrolyzer cell (c), and fuel synthesis unit (d)	Cooling, heating, electricity, and hydrogen/synthetic methane	Lowest total cost rate (14.9 \$/h) is for model (a), highest exergetic efficiency (62.8 %) and highest net power output rate, but lowest total product cost (19.8 \$/GJ) is for model (b)	(Habibollahzade et al., 2021b)
Municipal solid waste	a fuel cell integrated with a proton exchange membrane cycle (a) or Vanadium chloride cycle (b)	Hydrogen and power	produced hydrogen in proton exchange membrane and Vanadium chloride= 293 kg/day and 585 kg/day, the system coupled with the Vanadium chloride cycle exhibits better performance than the system with proton exchange membrane	(Cao et al., 2022b)

studied in power plants and polygeneration systems. In the two previous subsections, each of these methods is discussed. In those articles, only one of these methods was used. In this section, systems with simultaneous use of digestion and gasification will be investigated. It should be noted that the number of research projects conducted in this field in recent years is limited and more investigations are necessary. The schematic of the cycle in Fig. 17 that was proposed by Ogorure et al. (2018) shows that the designed system in this research uses both methods of gasification and anaerobic digestion of biomass to produce power and cooling along with the solid oxide fuel cells, Refrigeration cycles, and turbines. This system, which was developed for a farm in Nigeria in reverse state, feeds on the biomass of the same area. The net power of this power plant is estimated 5.226 MW, which is able to supply the required electricity of the farm (4.826 MW), and also the excess electricity produced can be used for other electrical networks.

Sorgulu and Dincer (2021) also developed a system that converts biomass through both anaerobic digestion and gasification. The products of this system include electricity and freshwater, in which the power is produced by a steam turbine, and freshwater is obtained by multi-effect desalination and reverse osmosis units. The innovation of this study is using hythane, a mixture of H_2 and CH_4, instead of biogas or syngas to improve the system performance from energy and environmental viewpoints. The schematic of this system is shown in Fig. 18. The production rate of power and freshwater obtained 4.49 MW and 92.29 kg/s, respectively.

Table 11 summarizes the features and findings of these two studies.

3.1.4. *Digestion-based plants vs. gasification-based plants*

In addition to studies that have investigated and used both of the mentioned conversion methods, there are also studies that have compared these two methods, and discussed their efficiency in some systems and configurations. This section refers to the following articles. In a study, Behzadi et al. (2018b) compared biomass conversion via gasification and anaerobic digestion for Tehran waste to energy power plant. Gasifier is used in model (a), and anaerobic digester is used in model (b). The results have shown that model (b) is more suitable than model (a), because, the energy efficiency of the model (b) is 1.2 % more than model (a), the net output power of the model (b) is 600 kW more than model (a), the optimal exergy efficiency of the model (b) is 1.04 % more than model (a), and the total unit cost rate at the optimal point for the model (b) is 1.75 \$/ GJ cheaper than model (a). Balafkandeh et al. (2019) designed a combined cooling, heating, and power system that is fueled by biomass. As shown in Fig. 19, they considered two different scenarios for biomass conversion: biomass conversion via gasification process; and biomass conversion via anaerobic digestion process. Then these two scenarios were evaluated and compared. Similarly, the results

Table 8
Summary of conducted studies on choosing the best working fluid for organic cycles.

Biomass	Devices	Outputs	Conclusion	Ref.
Paper	a biomass gasification process, an ejector refrigeration loop, a proton exchange membrane electrolyzer, and a dual organic Rankine cycle with several working fluids (R245fa-R134a, R236fa-R1234yf and R600-R290)	Syngas, power, refrigeration effect, heating load, hydrogen, and oxygen	maximum improvement in hydrogen cost and environmental impact per unit exergy are within 49.18 % and 34.58 % for R236fa-R1234yf, highest energy and exergy efficiencies= 79.35 % and 67.64 % for R600-R290 usage, R600-R290 leads to the minimum total product cost and environmental impact rates by about 152.7 % and 485.1 Pts/h, the highest improvement in the total cost rate belongs to R245fa-R134a by 39.5 %, the environmental impact rate is improved within R236fa-R1234yf for 34.69 %	(Boyaghchi et al., 2018)
Municipal solid waste	the waste gasification unit, the Rankine cycle, and an organic Rankine cycle with several working fluids (R123, n-heptane, R11, R141-b, isohexane, R717)	Power	The highest performance achieved using R123, optimum exergy efficiency and total product unit cost= 19.61 % and 24.65 $/GJ	(Behzadi et al., 2018a)
N.M	a gasifier, PEM fuel cell, a multi-effect desalination unit, and a series two-stage organic Rankine cycles using various zeotropic mixtures (R600a-R601a, R601a-Hexane, R601a-C2Butene, R134a-R245fa, R113-R114)	Heat, power, and freshwater	the highest exergy efficiency and lowest total cost rate is for using of R601a-C2Butene with the values of 24.56 % and 65.16 $/h	(Fakhari et al., 2021)

of this study showed that anaerobic digestion is more desirable than gasification in terms of efficiency, unit product cost, and environmental impacts.

Cao et al. (2022c) studied the utilization of anaerobic digestion and gasification methods for biomass conversion in a cogeneration system for producing electricity and hydrogen. The results have been presented from energy, exergy, and environmental viewpoints. The anaerobic digestion-based system is more suitable because it produces more electricity and hydrogen, has a higher exergy efficiency and lower CO_2 emissions. But from the economic viewpoint, the gasifier-based system seems more suitable. Considering this issue, one of the two methods cannot have priority over the other in this configuration, and choosing the system depends on the criteria of the decision makers. Table 12 presents a summary of the systems mentioned in this section.

3.1.5. *Other studies*

In addition to the articles that were reviewed in the previous subsections, there are also articles in the field of biomass-based polygeneration systems that did not place into the common categories that were mentioned earlier. The integration of gasification units with some other units in order to increase energy efficiency, the production of diverse products, and the use of waste in a useful way have attracted the attention of many researchers. The integration of biomass gasification unit with compressed air energy storage (CAES) systems can be seen in two cases of studies conducted in recent years (Razmi et al., 2021; Xue et al., 2022) have studied the combination of CAES and gasification units. They indicated that with this integration, the system's overall efficiency improves 0.35 %. The integration of biomass gasifier with thermoelectric generator (Khanmohammadi et al., 2019) and carbon capture and storage unit (Ghiat et al., 2020) have been investigated in recent years papers.

To produce power and heat without carbon emissions, one of the novel approaches that has been studied, is chemical looping combustion. Sikarwar et al. (2020) combined this technology with the biomass-based power plant integrated by the organic Rankine cycle.

In addition to the studies that focused on the simulation of biomass-base plants, the research projects that studied these plants on a laboratory scale are also seen in recent years' papers (Al Asfar et al., 2020).

The issue of energy is not exclusive to industries and power plants. High energy demand in the city has created the concept of "*energy building*". Supplying the power, heating, and cooling requirements of buildings in an efficient way has been the focus of many researchers. Energy supply using renewable energy sources is the topic of numerous recent research projects. Among the articles that have investigated biomass-based systems in recent years, there have been some papers in the field of building energy (Jabari et al., 2018, 2019; Mohammadikhah et al., 2021; Sadi et al., 2021).

In this section, the recent researches in the field of biomass-based systems were reviewed. The systems were classified into two categories from a general viewpoint and based on the method used to convert biomass: systems that use the gasification method and systems that use anaerobic digestion. The articles related to these two categories, the articles that have used these methods simultaneously, and the articles that have studied the comparison of these two methods were also reviewed and mentioned separately. In addition, the articles that belonged to the category of gasifier-based systems (considering that they included a large number of articles) were classified based on the products they produce, and similar items were mentioned together. Fuel cell-based systems were reviewed separately in the same section due to the special importance of them in research projects. In the review papers mentioned above, new systems and their innovations were implemented, and some of the most important results were mentioned, also more features and main results were presented through tables. Important factors affecting the behavior of systems will be discussed in more detail in the following subsection.

3.2. *Study of the effect of biomass-dependent parameters on the system*

This section addresses the influence of important parameters on the performance of biomass-based polygeneration systems. Since the main focus of the current article is on biomass, only factors related to biomass,

Table 9
Summary of conducted studies on choosing the best agent for gasification.

Biomass	Devices	Outputs	Conclusion	Ref.
Wood, Paper, Municipal solid waste, and Sawdust	Gasifier (using four gasification agents: air, oxygen-enriched air, oxygen and steam)	Hydrogen	Highest hydrogen production rate is obtained by steam, oxygen, oxygen-enriched air and air, respectively. highest value of energy efficiency and highest exergy efficiency are associated with air gasification and steam gasification	(Shayan et al., 2018)
Municipal solid waste	biomass gasification (using four gasification agents: air, oxygen-enriched air, oxygen and steam) integrated internal reforming solid oxide fuel cell plant	Heat and power	most economic electricity and power rate is obtained by oxygen, also using this agent causes eco-friendliest case based on the CO_2 emission rate	(Hosseinpour et al., 2020)
Municipal solid waste	proton exchange membrane fuel cell, organic Rankine cycle, thermoelectric generator, and gasifier (using air and steam agents)	Power, heat and hot water	Steam is better choice due to having 6.68 % higher net output power, 1.7 % lower total cost rate, 2.49 % higher energy efficiency, 0.65 % higher exergy efficiency, 0.242 t/MWh lower value of CO_2 emission index. Optimum net power generation and total cost rate for steam gasification= 1.849 kW and 5.0942 $/h	(Behzadi et al., 2020)
N.M.	Gasifier (using air, O2, O2-enriched air, steam, CO2, and a mixture of these agents)	Syngas	For the final optimization the exergy efficiency and cold gas efficiency for steam gasification are 93.7 % and 94.8 %. the corresponding values for CO_2 gasification are 94.7 % and 75.8 %. furthermore, CO_2 gasification consumes more CO2 than it emits	(Habibollahzade et al., 2021a)
Timber and wood waste	Gasification (using two agents of air and a mixture of air-steam) integrated with water gas shift reactors and product recovery unit	Hydrogen	for all studied temperatures produced hydrogen through the air-steam gasification is at the highest points.	(Safarian et al., 2022)

such as moisture content, mass flow rate, gasifier temperature, etc., are evaluated. Since two important biomass conversion methods were investigated in the present article, each of these methods is discussed in separate subsections. For more information about the papers that will be reviewed, refer to the previous sub-sections or use Tables 4–12.

3.2.1. *Anaerobic digestion-based plants*

As discussed in the previous sections, anaerobic digestion is one of the biomass conversion methods, which makes the biomass suitable for use as an energy source by converting it into biogas. Some of the most significant factors that can affect the performance of biomass-based anaerobic digestion systems are listed and discussed below, and some of the diagrams presented in the papers are also given. Of course, it should be noted that the arguments used are generally correct; but depending on the system configuration and other important factors, the opposite of what has been described may be observed in some cases.

- Biogas quality (the molar fraction of methane in biogas)

Due to the high energy content of methane along with an increase in the quality of biogas, its heating value increases; thereby, the overall energy and exergy efficiency, as well as the flow rate of the system's products, increase. Safari and Dincer (2019) showed an increase in the molar fraction of methane from 0.4 to 0.8, increases the heating value of biogas, the overall energy efficiency, and the overall exergy efficiency from 9766 to 29,659, from 55 % to 76 %, and from 73 % to 45 %, respectively. Fig. 20 shows the effect of biogas quality in the mentioned research on the overall efficiency of the system and subsystems.

- Mass flow rate of inlet biomass

By increasing the biomass feed into the system, the enthalpy of inlet fluid increases, thereby the net output power and the system's overall efficiency increase. Sevinchan et al. (2019) showed that an increase in the rate of biomass feed from 10^5 to 1.5×10^5 kg/day increases the power generation rate from 1000 to 1394 kW.

Among the articles reviewed in the selected timescale by the authors, only these are the ones that have investigated the effect of these parameters on biomass-based anaerobic digestion systems' performance; of course, the small number of articles related to the use of anaerobic digestion is also the reason for this lack, so it seems crucial to conduct more studies in this field.

3.2.2. *Gasification-based plants*

The gasification process, as the most widely used conversion method used in the articles, can be influenced by several factors and affect the performance of the entire system. Some of the most important factors investigated in the recent studies are listed and analyzed below. It is reemphasized that the explanations mentioned to approve the behavior of the system against parameter change are generally acceptable, and specific conditions or different configurations may provide other results.

- Mass flow rate of inlet biomass

The main feedstock of biomass-based polygeneration systems is the inlet biomass into the system. Therefore, by increasing the rate of inlet biomass, the production of useful products, increases in the system. In the research conducted by Yilmaz et al. (2019), increasing the mass rate of biomass from 0.72 to 10.72 kg/s increased the hydrogen production rate by 0.12 kg/s. Also, in a study by Yuksel et al. (2020), with an increase in the biomass flow rate from 2.94 to 7.94 kg/s, the hydrogen production rate doubled, and the power production rate reached to 19, 557 from 5719 kW. The references (Onder et al., 2020; Yuksel et al., 2019; Yilmaz et al., 2020; Safder et al., 2021; Houshfar, 2020) also indicate the same effect. For example, the diagram presented by Yilmaz et al. (2020) shows this effect in Fig. 21 clearly.

The efficiency of polygeneration systems is also affected by the inlet mass flow rate. Increasing the mass flow rate of biomass, raises input enthalpy, and the more enthalpy enters the cycle, increases the input and then the output energy of cycle; as a result, the energy efficiency improves. Yuksel et al. (2019) showed that by increasing the mass rate of biomass from 10 to 26 kg/s, the overall system's energy efficiency increases from 58 % to 66 %. In another study conducted by Siddiqui and Dincer (2021) an increase in the rate of inlet biomass from 0.5 to 2.2 kg/s increases energy efficiency from 65.2 % to 69.2 %. The same behavior can be seen in references (Yilmaz et al., 2019, 2020; Yuksel et al., 2020). However, in the research of Safder et al. (2021) the results are different, so an increase in the mass flow rate of biomass from 1.5 to 10 kg/s led to a decrease in energy efficiency from 97.47 % to 63.92 %. It is obvious that the increase in output energy has not been able to keep pace with the increase in input energy. The reason for this should be further investigated. It seems that the existence of studies is necessary to reach a consensus of opinion.

According to the increase of useful output products and net output work, exergy efficiency is also influenced by the input biomass rate.

Table 10
Summary of conducted studies on choosing the best biomass feed for system.

Biomass	Devices	Outputs	Conclusion	Ref.
Pine sawdust, Fowl manure, Municipal solid waste	biomass gasifier, solid oxide fuel cell, gas turbine cycle and a Rankine cycle	Power	Pine sawdust causes the best thermodynamic and economic performances, Fowl manure causes the best environmental performance	(Ghaffarpour et al., 2018)
Wood, Paper, Rice husk	downdraft type biomass gasifier, solid oxide fuel cell, externally fired gas turbine, and Stirling engine	Power	the best performances belong to rice husk, wood, and paper fueled system, respectively.	(Roy, 2020)
Pine sawdust, groundnut shell, Rice straw, Rice, husk, Eucalyptus, Sunflower shell, Sugarcane bagasse	solid oxide fuel cell, gasifier, and high-temperature sodium heat pipes	Power	Eucalyptus had the best performance followed by pine sawdust, Sunflower shell, groundnut shell, rice straw, sugarcane bagasse, and rice husk	(Mojaver et al., 2020)
Wood, Sawdust, Pine bark, Torrefied pellet, Straw, Cotton stalk, and Bagasse	biomass gasification, molten carbonate fuel cell, an externally fired gas turbine, and a supercritical carbon dioxide cycle	Power	η_{max}= 40.88 %, ψ_{max}= 34.07 %, maximum Ex_d at gasifier, minimum cost of electricity= 0.1602 $/kWh, maximum CO_2 emission reduction potential= 1510 ton of CO_2/year, maximum environmental benefit= 21,901 $/year	(Roy et al., 2020a)
Wood, Paper, Municipal solid waste, Paddy husk, Olive refuse, Legume Straw	solid oxide fuel cell, gas turbine, organic flash cycle, and a thermoelectric generator	Power	maximum energy efficiency belong to paddy husk, municipal solid waste, and paper fueled system, respectively. maximum exergy efficiency belong to municipal solid waste, paper, and wood fueled system, respectively. maximum Ex_d at air heat exchanger, according to the base simulation condition, the system can achieve to 49.37 % and 42.496 % energy and exergy efficiency.	(Teng et al., 2021)
Municipal solid waste, wood, paper, sawdust	biomass gasifier, solid oxide fuel cell, gas turbine, a thermoelectric generator, a multi-stage flash desalination with brine recirculation unit, and a CO_2 capture unit	power and freshwater	Municipal solid waste causes the best environment and economic performances, total product cost, and environmental impact rate are obtained by this biomass are 2.106 $/h and 14.97 Pts/h. maximum produced freshwater and power are obtained by 46.05 m^3/day, and 228.7 kW for wood and sawdust. minimum levelized CO_2 emission = 0.138 ton/MWh for sawdust.	(Mehrabadi and Boyaghchi, 2021)
Bean straw, oats strand, rapeseed, wheat straw, and alfalfa	gasifier, boiler, vapor generator, mixture, turbine, separator, condenser, expansion valve, evaporator, pump, heater	Power and cooling	For bean straw: $\eta = 23.3$ % and $\psi = 10.1$ %, for oats strand: $\eta = 25.2$ % and $\psi = 11$ %, for rapeseed: $\eta = 21.6$ % and $\psi = 9.5$ %, for wheat straw: $\eta = 23.6$ % and $\psi = 10.3$ %, for alfalfa: $\eta = 26.6$ % and $\psi = 11.4$ %, moreover exergoenvironment factor, effectiveness factor of environmental damage, and exergy stability factor of the base case (bean straw)= 0.83, 8.25, and 0.89	(Cao and Ehyaei, 2021)
Municipal solid waste, Paper, Paddy husk, Wood	Rankine cycle, a multi-effect desalination, and a solid oxide electrolyzer cell	Power, freshwater, and hydrogen	the highest exergetic efficiency, maximum freshwater production rate, greatest hydrogen generation capacity, and minimum cost of products are referred to the municipal solid waste with 16.72 %, 2.69 kg/s, 12.05 kg/h, and 16.94 $/GJ.	(Xu et al., 2022)
Rice husk, Bagasse, Furniture waste	an externally fired gas turbine, post combustion CO_2 capture employing molten carbonate fuel cell and waste heat recovery through steam cycle and organic Rankine cycle	Power production with CO_2 capture	For rice husk: $\eta = 48.25$ % and $\psi = 40.97$ %, for bagasse: $\eta = 42.55$ % and $\psi = 36.71$ %, for furniture waste: $\eta = 32.61$ % and $\psi = 28.48$ %, moreover Levelized electricity price for rice husk, bagasse, and furniture waste= 0.1018, 0.1034, and 0.111 $/kWh. The maximum power generation, energy efficiency, exergy efficiency, and annual CO_2 capture that can be achieved by this plant are 16.21 MW,50.8 %, 43.2 %, and 112,400 tons.	(Zaman and Ghosh, 2022)

According to the results presented from the work of Yuksel et al. (2019) an increase in the rate of inlet biomass by 16 kg/s increased the exergy efficiency by approximately 8 %. The results of another study by Yuksel et al. (2020) indicate that an increase in the rate of inlet biomass from 2.94 to 7.94 kg/s led to an increase in exergy efficiency from 52.71 % to 61.8 %. This direct relationship between biomass flow rate and exergy efficiency can be seen in references (Yilmaz et al., 2019, 2020; Onder et al., 2020; Siddiqui and Dincer, 2021). However, in three cases between the reviewed articles, different results were observed; references (Safari and Dincer, 2022; Rashidi and Khorshidi, 2018; Safder et al., 2021) showed that an increase in the rate of inlet biomass causes a decrease in exergy efficiency. This difference is mainly because the increase in net output power is not greater than the increase in energy entering the system, and a major part of the input energy is wasted. But still, more detailed investigations are suggested. Fig. 22, in the article by Yuksel et al. (2019), shows the effect of the inlet biomass rate on the overall system and subsystems' energy and exergy efficiencies.

- Moisture content of biomass

  The amount of moisture in the biomass is one of the prompting factors on the main features of the system. As the moisture content of biomass increases, the lower heating value of biomass decreases, so the net power output from the turbines decreases; in this way, the net output work and exergy efficiency of the systems decrease.
- Gasification temperature

An increase in the gasifier temperature increases the heating value of the produced syngas, then the thermal energy input to the cycle rises, so the plant reaches a higher temperature, and the waste heat enters the different subsystems with a higher enthalpy rate, as a result, the production rate of the system's useful products and its efficiency increases. Due to the endothermic nature of hydrogen production reactions, high

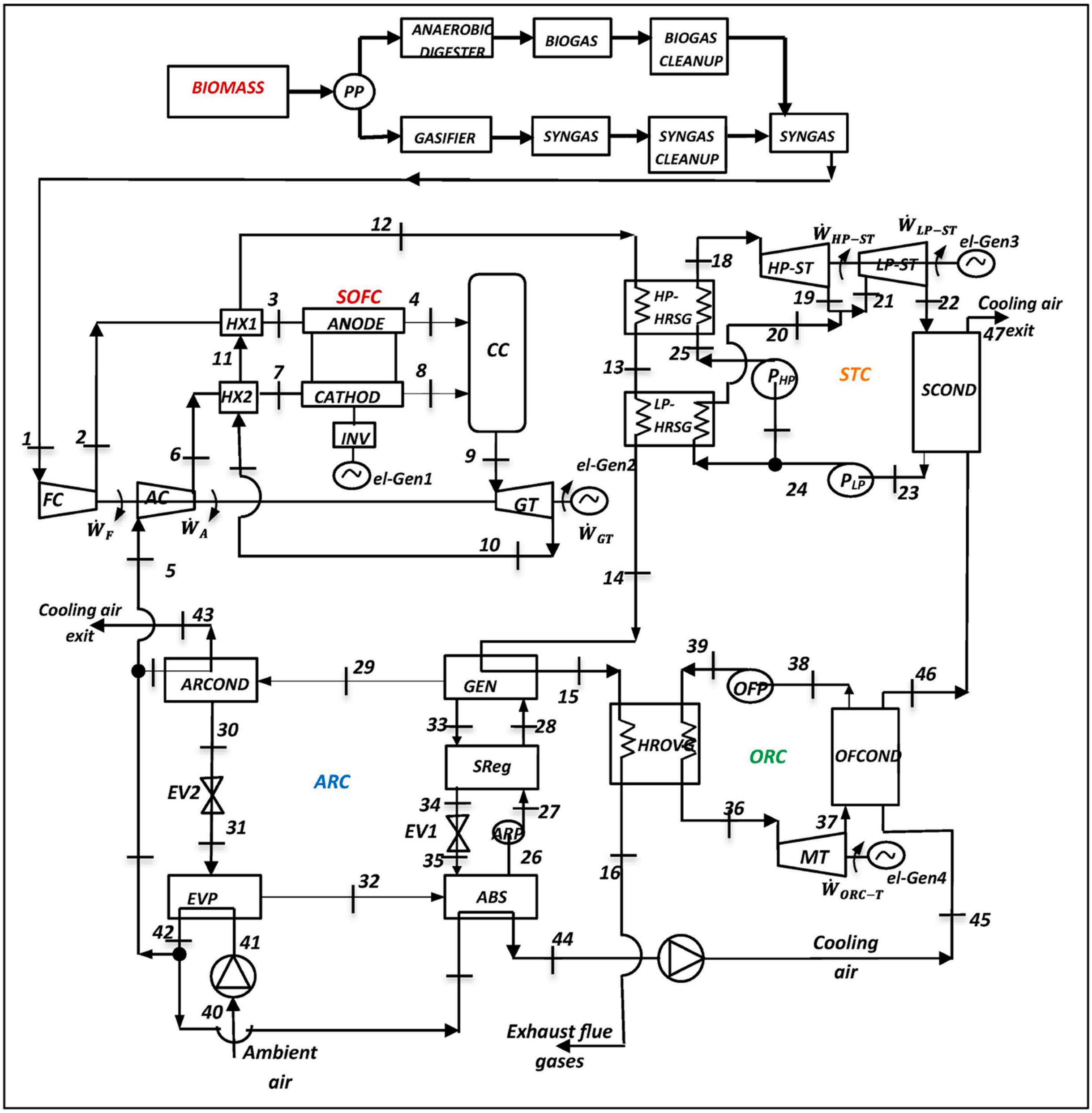

Fig. 17. A The schematic of the cycle with simultaneous use of digestion and gasification proposed by Ogorure et al. (adapted from Ogorure et al. (2018)).

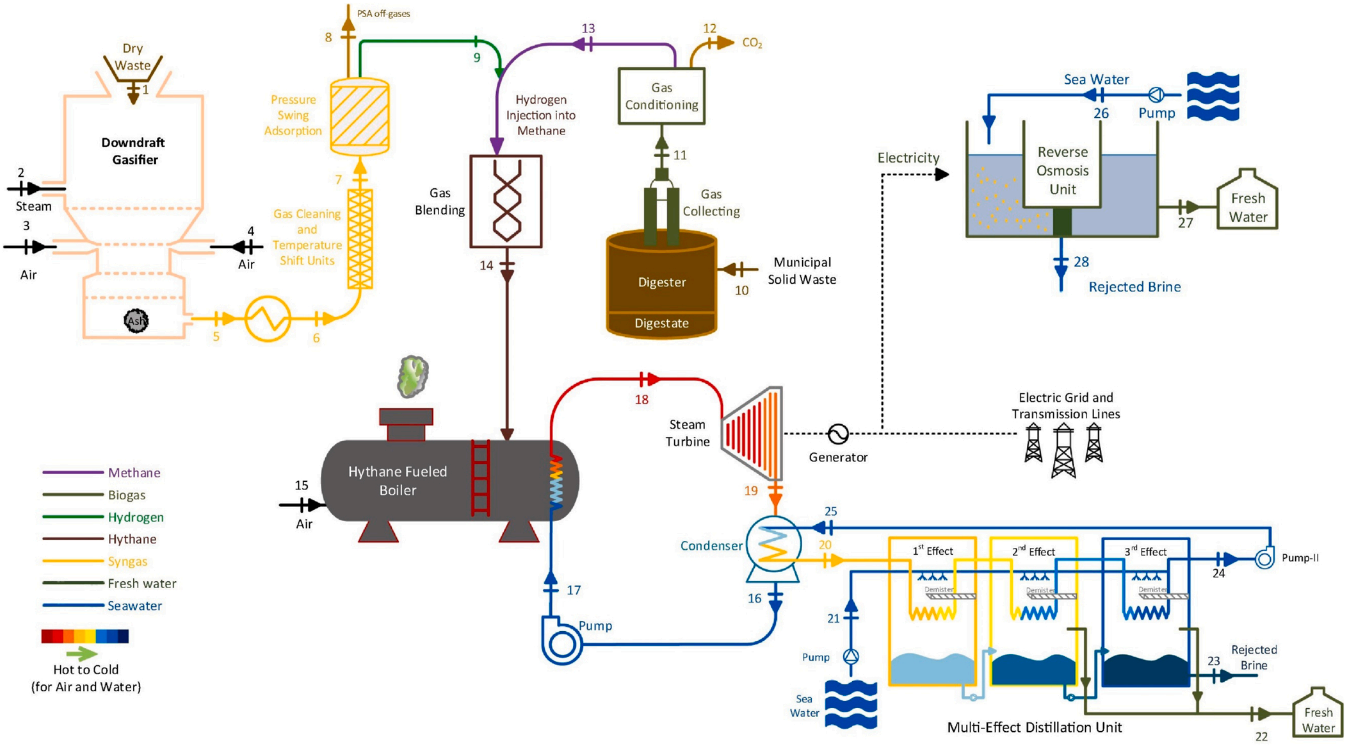

Fig. 18. A The schematic of the cycle with simultaneous use of digestion and gasification proposed by Sorgulu et al. (adapted from (Sorgulu and Dincer, (2021)).

Table 11
Summary of studies on biomass-based plants with simultaneous use of digestion and gasification.

Biomass	Devices	Outputs	Conclusion	Ref.
agro-wastes	solid oxide fuel cell stack, gas turbine, steam turbine, gasification and digestion subsystems, organic Rankine and absorption refrigeration cycles	Electrical energy, and refrigeration	$\eta = 63.62$ %, $\psi = 58.46$ %, maximum Ex_d at combustion chamber, Life cycle cost= 3.753 million$, breakeven point= 7.5 years, unit energy cost= 0.0109 $/kWh, specific emission of CO_2 = 141.2 kg/MWh, sustainability exponent= 3.65	(Ogorure et al., 2018)
Municipal wastes and olive oil waste	multi-effect desalination, reverse osmosis, gasification, and digestion subsystems	Electricity and freshwater	$\eta = 37.04$ %, $\psi = 19.78$ %, maximum Ex_d at gasifier	(Sorgulu and Dincer, 2021)

temperature increases hydrogen production too (Zhang et al., 2019). Yuksel et al. (2020) showed that an increase in the gasifier temperature from 525° to 725°C increases the energy efficiency, exergy efficiency, power production rate, and hydrogen production rate from 53.66 %, 48.83 %, 7030 kW, and 0.016 kg/s to 58.69 %, 56.86 %, 17,870 kW, and 0.041 kg/s. In the research conducted by Yilmaz et al. (2020) the results showed that an increase in the gasification temperature from 520° to 680°C leads to an increase in exergy efficiency from 45.08 % to 49.21 % and also an increase in hydrogen production by 0.03 kg/s. The diagram presented in this paper is shown in Fig. 23. In addition, according to the results obtained from the study of Onder et al (Onder et al., 2020). if the gasifier temperature increases by nearly 500 °C, the hydrogen production rate increases by 0.033 kg/s. Yilmaz et al. (2019) showed in another article that if the temperature of the gasifier from 688 reaches 1088 °C, the power generation rate of the system increases from 11,000 kW to 13,500 kW. The results reported in (Cao et al., 2021a; Sotoodeh et al., 2022; Yuksel et al., 2019; Hamrang et al., 2020; Xu et al., 2022; Zhang et al., 2019) also confirm this effect. But among the articles of recent years in this field, four studies reported different results; in the references (Safari and Dincer, 2022; Roy et al., 2020a, 2019; Khanmohammadi and Atashkari, 2018), the exergy efficiency has decreased with an increase in the gasification temperature. Reasons such as the difference between the input and output exergy of the system due to the increase in temperature, the configuration of the system in such a way that the production of net output power does not increase sufficiently, the high loss of exergy in the devices and things like that can cause this to happen. So, more studies are required to reach a consensus of opinion and detailed investigations.

In this part, three of the most important parameters that affect the main characteristics of biomass-based polygeneration systems were discussed. Some other factors, such as the effect of equivalence ratio and the size of biomass components, have been less studied by researchers. It should be noted that the papers that investigated the impact of biomass type, system configuration, agent type, and working fluid of the Rankine cycle on the system performance were reviewed in part 3.1.2 of the article.

4. Discussion

Energy, drinking water, environment, and sustainability are the most serious challenges in today's world. Despite the proven damages of fossil fuels, such as the severe reduction of fossil reserves, global warming, and air pollution most of the world's countries still rely on these fuels (Saini et al., 2021). The use of renewable energy based polygeneration systems, as discussed in the previous parts, is one of the best solutions that, while preventing current challenges, leads to solving them and drawing

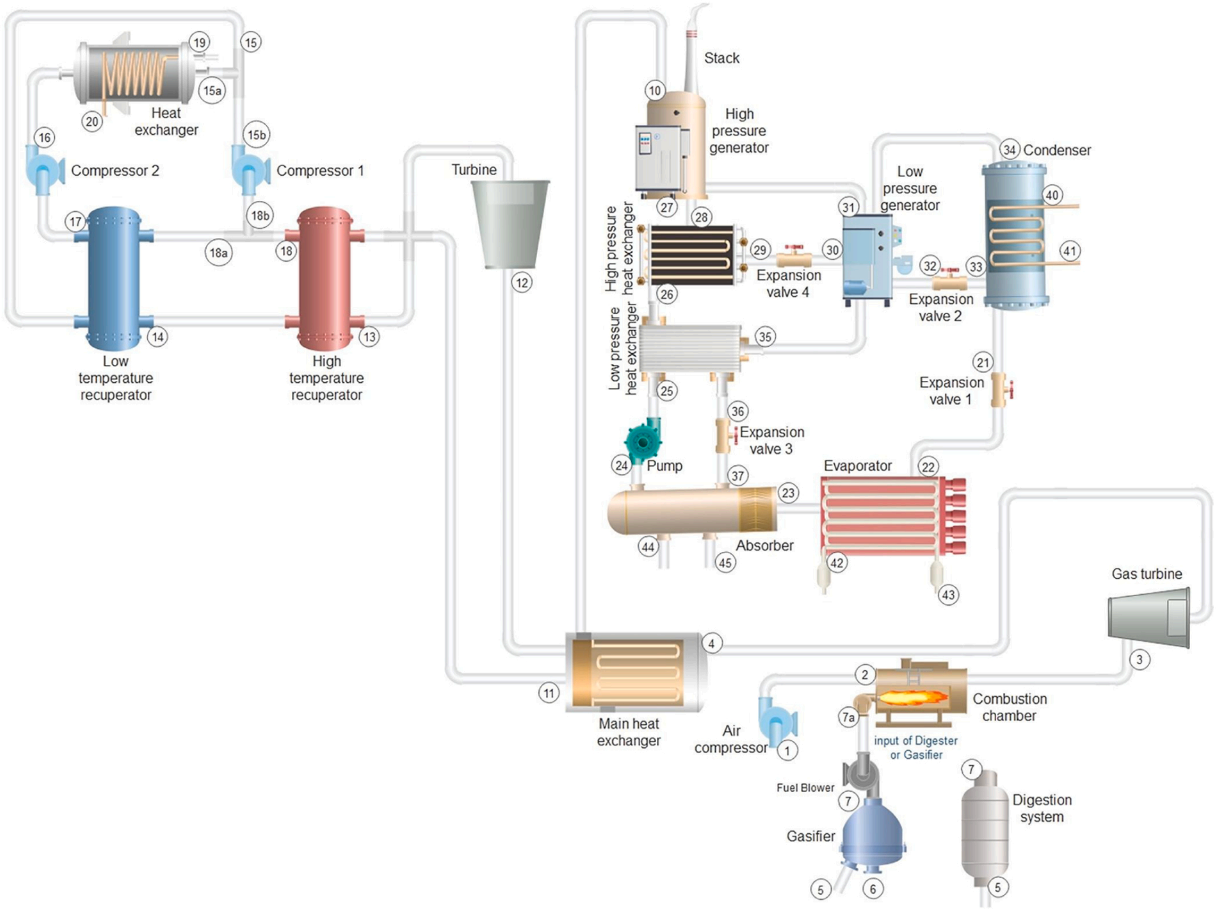

Fig. 19. A CCHP system fueled by biomass, comparing digestion/gasification (adapted from Balafkandeh et al. (2019)).

a sustainable future. In addition, due to the importance of biomass as a renewable source of energy, in this article, a review of biomass based polygeneration systems was conducted to provide a summary of recent studies and summarize their characteristics and results. In the previous parts, the introduction and presentation of these articles were argued. In this part, a general overview of the papers, the outlooks, and challenges related to these systems are discussed.

4.1. General overview

As previously discussed in more detail, one of the solutions suggested and investigated by researchers for current problems, is using biomass as a clean fuel in polygeneration systems. But due to the existence of advantages and disadvantages of the present strategy, a review on the existing studies and suggestions seems essential.

In the present article, after introducing these systems and topics related to their analysis, a detailed review of existing literature was done in Section 3. The results showed that gasification and anaerobic digestion are the most popular biomass conversion methods in the articles, and among these two, gasification has the greatest number of articles. Integration of fuel cells with such systems has also attracted the attention of many researchers. In addition, many studies for assessment and comparison of different situations have been investigated in the articles of recent years. Moreover, articles related to simultaneous use of anaerobic digestion and gasification, and also the comparison of these two methods have been presented. Also, other studies that examined the integration of new subsystems or designed these polygeneration systems for energy buildings, have been presented.

Numerous analyses, single-objective and multi-objective optimizations, and parametric studies using different software have been used in the studies to select the best conditions. Table 13 summarize the analyses performed in those articles along with the software used by them. It should be noted that in this table En., Ex., Ec., Env., and M.O.Opt refer to energy, exergy, economic/exergoeconomic, environmental/exergoenvironmental, and multi-objective optimization, respectively.

In addition to these papers, studies that have investigated advanced exergy analysis have a special place. Advanced exergy analysis, during calculating exergy efficiency and exergy destruction rate of systems, can find the real potential of system improvement. Splitting exergy destruction into exogenous/endogenous and avoidable/unavoidable parts provides a new development in exergy analysis of systems that facilitates system improvement (Soltani, 2019). Further investigations and studies of systems through advanced exergy analysis for biomass-based systems seem necessary. In addition, predicting the behavior of energy systems by machine learning algorithms is a new topic that appears in some articles (Khanmohammadi et al., 2022; Ozbas et al., 2019) and can provide a new and significant perspective in the analysis of the systems.

The study of discussed articles from energy and exergy standpoints shows that the energy efficiency in different systems was nearly between 27 % and 92.10 %, and the exergy efficiency was between 15.61 % and 77.49 %. Therefore, exergy efficiency is lower than energy efficiency, which is a reasonable result (Kasaeian et al., 2020). If the ten systems with the highest energy efficiency compared to the rest of the systems are arranged respectively, the results are presented in the Table 14, also the ten systems with the highest exergy efficiency compared to other systems are given in Table 15. According to what is presented in

Table 12
Summary of studies on comparing digestion/gasification-based systems.

Biomass	Devices	Outputs	Conclusion	Ref.
Municipal solid waste	waste gasification unit (gasifier (a)/digester (b)) and the Rankine cycle	Power	$\psi_{opt,a} = 17.98$ %, $\psi_{opt,b} = 19.02$ %, maximum Ex_d at gasifier and combustion chamber in the models (a) and (b), optimum total product unit cost = 28.31 $/GJ and 27.68 $/GJ in the models (a) and (b)	(Behzadi et al., 2018b)
Woody biomass	Gasifier (a)/ digester (b), gas turbine, supercritical carbon dioxide cycle and double effect LiBr-H2O absorption chiller	Cooling, heating, and power	the exergy efficiency of model (b) is higher than that of the model (a) by more than 13 %, $\psi_{opt,b} = 47.09$ %, optimum product unit cost in model (b)= 5.436 $/GJ, CO_2 emissions in the models (a) and (b)= 2.6×10^{-2} t/ MWh and 4.21×10^{-2} t/ MWh	(Balafkandeh et al., 2019)
Municipal solid waste	Gasifier (a)/ digester (b), a micro-scale gas turbine, an absorption power cycle for exhaust waste heat recovery of the gas turbine, and an alkaline electrolyzer	Power and hydrogen	$\psi_{opt,a} = 39.20$ %, $\psi_{opt,b} = 41.70$ %, optimum CO_2 emissions in the models (a) and (b)= 0.847 kg/ kWh and 0.593 kg/ kWh, optimum Levelized cost of product= 0.0537 and 0.0653 $/kWh in the models (a) and (b), system cost rate in the models (a) and (b)= 44.03 and 58.18 $/h	(Cao et al., 2022c)

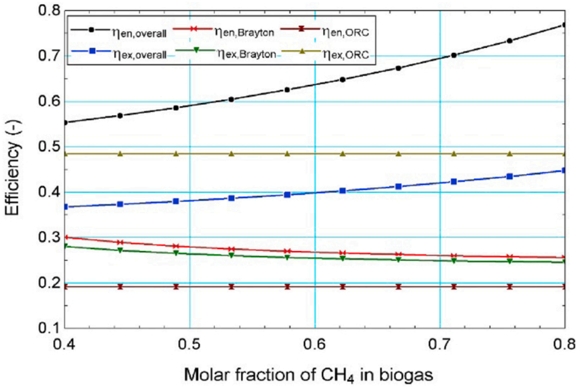

Fig. 20. Effect of CH_4 molar fraction on efficiencies presented by Safari et al. (adapted from Safari and Dincer (2019)).

Tables 14 and 15, the most efficient systems in terms of energy efficiency range from 66.4 % to 92.10 % and the most efficient systems in terms of exergy efficiency range from 52.6 % to 77.49 %.

According to Tables 14 and 15, it seems that the use of anaerobic digestion method is more effective in improving energy efficiency than exergy efficiency. Anaerobic digestion method has been used in systems with high energy efficiency, while gasification method has been used in systems with high exergy efficiency. By comparing the type of biomass used as feed for systems, it can be seen that the use of municipal solid waste and wood as the biomass feed is more common among systems with high energy efficiency, and the use of municipal waste is more common in systems with high exergy efficiency. The main products of the high energetic efficient systems, included power, heating, and cooling, followed by some other products such as hydrogen, freshwater, oxygen, syngas, and refrigeration. Also, the main products of the high exergetic efficient systems, are power, heating, cooling, and hydrogen, followed by some other products such as drying, freshwater, oxygen, refrigeration, and syngas.

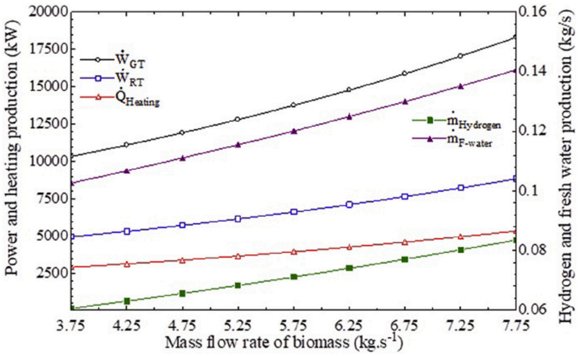

Fig. 21. Effect of mass flow rate of biomass on production rates presented by Yilmaz et al. (adapted from Yilmaz et al. (2020)).

If we specify the common studies among the top-ten of studies with the highest energy efficiency and the top-ten of studies with the highest exergy efficiency, there are two systems that were in both groups (Safder et al., 2021; Boyaghchi et al., 2018). These two articles, with a summary of their system features, are presented in Table 16. Safder et al. (2021) have proposed a system that is significantly more efficient than other systems both in terms of energy and exergy. This system has been widely analyzed, and multi-objective optimization has also been implemented on it. A schematic of the cycle suggested by them is presented in Fig. 24. In addition, Boyaghchi et al. (2018), during a comparative study, investigated the use of different working fluids for their system and reported the highest energy efficiency and exergy when using R290-R600 as the working fluid. The schematic of this system is also presented in Fig. 25.

4.2. Restrictions and future directions in biomass-based polygeneration systems

In this sub-section, an attempt has been made to discuss the challenges and limitations of biomass-based systems, as well as the proposed solutions to solve them in the future. These items are summarized below:

- According to the review which has been done on the articles, the high exergy destruction rate in gasifiers has been the most problem in all of the systems. High irreversibility decreases efficiency and increases costs. Solutions should be proposed and fully studied in order to reduce the rate of exergy destruction of gasifiers in biomass-based polygeneration systems to make it possible to design and use more efficient systems. Reactions carried out in the gasifier cause the destruction of exergy structures and break them into small irregular pieces, and it damages the biomass chemical exergy at high gasification temperatures. Therefore, the change of operational conditions, despite being effective, does not cause significant effects, because it cannot improve the irreversibility caused by the inherent destruction of material energy in the gasification process (Xiang et al., 2015). Solutions like torrefaction or removal of biomass moisture can reduce irreversibility and the effect of these factors to some extent. But this pretreatment itself may increase energy consumption and cause related irreversibility. Other methods

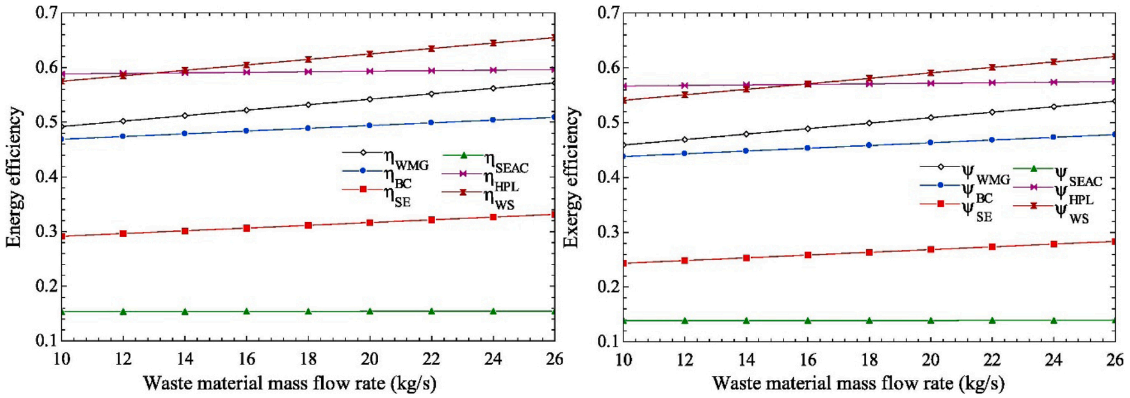

Fig. 22. Effect of biomass flow rate on efficiencies presented by Yuksel et al. (adapted from Yuksel et al. (2019)).

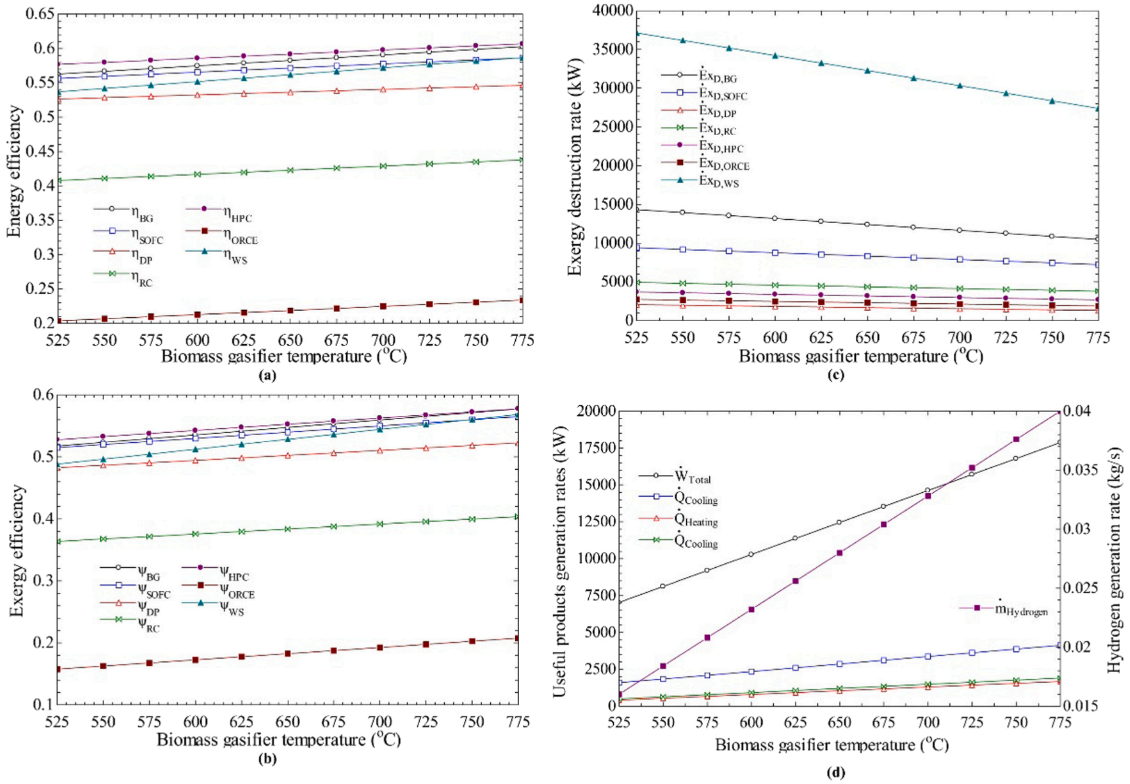

Fig. 23. Effect of biomass gasifier temperature on efficiencies and production rates presented by Yilmaz et al. (adapted from Yilmaz et al. (2020)).

such as gasification combined with situ reforming (Buentello-Montoya and Zhang, 2019), using CO_2 gasification agent, adoption of alothermal gasification (Karl and Pröll, 2018), multi-stage gasification, and chemical looping gasification can be suitable solutions to reduce the exergy destruction of the gasifiers (Li et al., 2021, 2022). However, the lack of more studies in this field is felt.

- -Various biomasses have been used as feedstock for polygeneration systems in the articles, but the use of municipal wastewater has received less attention. The way of disposal of wastewater has particular importance, and the discharge of wastewater into the seas in some areas has seriously damaged the environment and the regional ecosystem, and has also neglected a potential source of energy. Designing suitable systems for the use of urban wastewater is a topic that can be given more attention by researchers in the future.
- Further study in the field of using artificial intelligence methods, machine learning algorithms, and multi-objective optimizations in improving the prediction of the behavior of energy systems can be significantly useful.
- Considering the high availability of biomass in different regions of the world and in different seasons of the year, using it as an energy source both in industry and in buildings is a desirable option, and more studies are needed to facilitate its use in buildings.
- The most common pollutants in syngas are tars. Due to their high ability to condense and polymerize, they often lead to corrosion and the formation of solid particles and cause damage to equipment. The type of gasifier, as well as the type of agent used, can be effective on tar formation. As it has already been discussed in detail, fluidized bed gasifiers reduce tar production. The rate of tar production in entrained flow reactors are zero, and plasma gasifiers are able to destroy tars strongly. In addition, the use of oxygen as an agent can

Table 13
The analyses performed on reviewed article.

Analysis					Software	Ref.
En.	Ex.	Ec.	Env.	M.O.Opt		
✓	✓	×	×	×	EES	(Safari and Dincer, 2019)
✓	✓	×	✓	×	N.M.	(Sevinchan et al., 2019)
✓	✓	×	×	×	EES	(Bamisile et al., 2019)
✓	✓	×	✓	×	EES	(Adebayo et al., 2022)
✓	✓	✓	×	NSGA- III	EES, MATLAB, Python	(Ifaei et al., 2022)
✓	✓	×	×	×	Cycle-Tempo	(Chattopadhyay and Ghosh, 2018)
✓	✓	✓	✓	MOBA	EES, MATLAB, COMFAR III	(Cao et al., 2021a)
✓	✓	✓	×	×	EES	(Ji-chao and Sobhani, 2021)
✓	✓	✓	×	×	N.M.	(Moharamian et al., 2018)
✓	✓	×	×	×	EES	(Farajollahi et al., 2022)
✓	✓	✓	✓	GA	EES, MATLAB	(Safari and Dincer, 2022)
✓	✓	×	×	×	EES, Aspen Plus	(Ishaq and Dincer, 2021b)
✓	✓	✓	✓	DE	N.M.	(Rashidi and Khorshidi, 2018)
✓	✓	✓	×	×	EES, Aspen Plus	(Ishaq et al., 2020)
✓	✓	×	×	×	EES, Aspen Plus	(Ishaq and Dincer, 2020)
✓	✓	✓	×	×	Aspen Plus	(Li et al., 2020)
✓	✓	×	×	×	EES	(Onder et al., 2020)
✓	✓	×	×	×	EES	(Sotoodeh et al., 2022)
✓	✓	×	×	×	EES	(Yuksel et al., 2019)
×	✓	✓	×	GA	EES, MATLAB	(Khanmohammadi and Atashkari, 2018)
✓	✓	✓	×	×	EES	(Yilmaz et al., 2019)
✓	✓	×	✓	×	EES	(Yilmaz et al., 2020)
✓	✓	✓	×	×	EES	(Hamrang et al., 2020)
✓	✓	✓	×	weighted NSGA-II	EES, MATLAB	(Safder et al., 2021)
✓	✓	×	×	×	EES, Aspen Plus	(Siddiqui and Dincer, 2021)
✓	✓	✓	×	GWO	N.M.	(Musharavati et al., 2022)
✓	✓	×	×	×	Aspen Plus	(Ishaq and Dincer, 2021a)
✓	✓	✓	✓	GA	EES, MATLAB	(Taheri et al., 2021)
✓	✓	×	×	×	Aspen Plus	(Li et al., 2021)
✓	×	×	✓	×	Aspen Plus	(Lak Kamari et al., 2021)
✓	✓	✓	×	×	Aspen Plus, FORTRAN	(Yan et al., 2019)
✓	✓	✓	✓	×	EES	(Roy et al., 2019)
✓	✓	×	✓	×	EES	(Salehi et al., 2019)
✓	✓	✓	✓	×	EES, MS Excel	(Owebor et al., 2019)
✓	✓	✓	✓	PSO	EES, MATLAB	(Cheng et al., 2021)
✓	✓	✓	✓	GA	MATLAB	(Sadeghi et al., 2018)
✓	✓	✓	×	GA	EES	(Karimi et al., 2020)
×	✓	✓	×	RSM	EES, Minitab	(Roy et al., 2020b)
✓	✓	×	×	×	EES	(Yuksel et al., 2020)
✓	✓	✓	✓	GA	EES, MATLAB	(Behzadi et al., 2019)
✓	✓	×	×	×	EES, Aspen HYSYS	(Ebrahimi et al., 2021)
✓	✓	✓	×	GWO	EES, MATLAB	(Chen et al., 2021)
✓	✓	✓	×	PSO	N.M.	(Ebrahimi et al., 2021)
✓	✓	✓	✓	GA	EES, MATLAB	(Habibollahzade et al., 2018)
✓	✓	✓	×	GA	EES, MATLAB	(Gholamian et al., 2018)
✓	✓	✓	✓	NSGA-II	EES	(Mehrabadi and Boyaghchi, 2019)
✓	✓	✓	✓	GA	EES, MATLAB	(Houshfar, 2020)
✓	✓	✓	×	×	N.M.	(Zare, 2020)
✓	✓	✓	×	GA	MATLAB	(Cao et al., 2021b)
✓	×	✓	×	×	MATLAB, Aspen Pinch	(Rahimi et al., 2021)
✓	✓	✓	✓	GA	EES, MATLAB	(Habibollahzade et al., 2021b)
✓	✓	✓	✓	cutting-edge	EES	(Cao et al., 2022b)
✓	✓	✓	✓	NSGA-II	EES	(Boyaghchi et al., 2018)
✓	✓	✓	×	GA	EES, MATLAB	(Behzadi et al., 2018a)
✓	✓	✓	✓	GA	EES, MATLAB	(Fakhari et al., 2021)
✓	✓	✓	✓	GA	EES	(Shayan et al., 2018)
✓	✓	✓	✓	×	EES	(Hosseinpour et al., 2020)
✓	✓	✓	✓	GA	EES, MATLAB	(Behzadi et al., 2020)
✓	✓	×	×	GWO	EES, MATLAB	(Habibollahzade et al., 2021a)
✓	×	×	×	×	Aspen Plus	(Safarian et al., 2022)
✓	✓	✓	✓	✓(N.M.)	EES	(Ghaffarpour et al., 2018)
✓	✓	×	×	RSM	EES, MATLAB, Minitab	(Roy, 2020)
✓	✓	×	✓	RSM	Minitab, VIKOR SOLVER	(Mojaver et al., 2020)
✓	✓	✓	✓	×	EES	(Roy et al., 2020a)
✓	✓	✓	✓	PSO	EES, MATLAB	(Teng et al., 2021)
✓	✓	✓	✓	NSGA-II	EES, MATLAB	(Mehrabadi and Boyaghchi, 2021)
✓	✓	✓	✓	×	EES	(Cao and Ehyaei, 2021)
✓	✓	✓	×	NSGA-II	EES, MATLAB	(Xu et al., 2022)
✓	✓	✓	✓	×	EES, Cycle-tempo simulation	(Zaman and Ghosh, 2022)
✓	✓	✓	✓	×	EES	(Ogorure et al., 2018)
✓	✓	×	✓	×	EES, Landfill Gas Emissions	(Sorgulu and Dincer, 2021)
✓	✓	✓	✓	GA	EES, MATLAB	(Behzadi et al., 2018b)
✓	✓	✓	✓	GA	EES, MATLAB	(Balafkandeh et al., 2019)
✓	✓	✓	×	GA	EES, MATLAB	(Cao et al., 2022c)
✓	×	×	×	×	Aspen Plus	(Razmi et al., 2021)
✓	✓	✓	×	×	EBSILON	(Xue et al., 2022)
✓	×	✓	×	GA	MATLAB	(Khanmohammadi et al., 2019)
✓	✓	✓	✓	×	Aspen Plus, Aspen Process Economic Analyzer	(Ghiat et al., 2020)
✓	✓	×	✓	×	Aspen Plus	(Sikarwar et al., 2020)
✓	✓	✓	✓	×	LabVIEW, Fluent	(Al Asfar et al., 2020)

reduce tar content, while using steam causes more tar production. The use of different types of gasifiers or different types of agents can affect different parameters, so it is necessary to conduct more extensive studies in this field.

5. Conclusions

The use of biomass, as the most available renewable energy source, in providing the system’s energy plays a key role in sustainable

Table 14
Summary of top ten systems with highest energy efficiency.

Biomass	Devices	Conversion method	Outputs	η	Ref.
Sugarcane bagasse	a bagasse-biomass based gasifier-Brayton cycle, a Rankine cycle, a Kalina cycle, an ejector refrigeration cycle, and a multi-effect desalination unit	Gasification	Power, freshwater, and cooling	92.10 %	(Safder et al., 2021)
Municipal wastewater	Wastewater treatment plant, anaerobic digester, combustion chamber, absorber, electrolyzer, compressor, gas turbine, rectifier, condenser, pump, evaporator	Anaerobic digestion	freshwater, power, cooling, heat, hydrogen, and oxygen	79.4 %	(Ifaei et al., 2022)
Paper	a biomass gasification process, an ejector refrigeration loop, a proton exchange membrane electrolyzer, and a dual organic Rankine cycle with several working fluids (R600-R290)	Gasification	Syngas, power, refrigeration effect, heating load, hydrogen, and oxygen	79.35 %	(Boyaghchi et al., 2018)
Wood	a gas turbine cycle, a supercritical CO2 cycle, and a Kalina cycle	Gasification	Heating and power	78.15 %	(Ji-chao and Sobhani, 2021)
Wood	s-CO$_2$ cycle, gasifier, combustion chamber, and a domestic water heater	Gasification	Heating and power	75.89 %	(Cao et al., 2021a)
Chicken manure and maize silage	two-stage biomass digester, open-type Brayton cycle, Organic Rankine Cycle, single-effect absorption chiller, heat recovery, water separation unit	Anaerobic digestion	Electrical power, heating power, cooling power and product water from flue gas	72.5 %	(Sevinchan et al., 2019)
Maize silage	a solid oxide fuel cell, a biogas digester subsystem, a cascaded closed loop organic Rankine cycle, a single effect LiBr-water absorption refrigeration cycle, and a proton exchange membrane electrolyzer	Anaerobic digestion	Electricity, domestic hot water, hydrogen, and cooling	69.86 %	(Adebayo et al., 2022)
Municipal solid waste	gasifier with a solid oxide fuel cell, Stirling engine	Gasification	Power	67.38 %	(Habibollahzade et al., 2018)
Municipal solid waste	gasifier with a solid oxide fuel cell, Stirling engine, proton exchange membrane electrolyzer	Gasification	Power and hydrogen	66.41 %	(Habibollahzade et al., 2018)
Rice husk	Biomass gasification, Brayton cycle, Absorption cooling cycle, Brine wastewater treatment system, Thermoelectric generator, Organic Rankine cycle	Gasification	Electricity, cooling, heating, and freshwater	66.4 %	(Siddiqui and Dincer, 2021)

Table 15
Summary of top ten systems with highest exergy efficiency.

Biomass	Devices	Conversion method	Outputs	ψ	Ref.
Sugarcane bagasse	a bagasse-biomass based gasifier-Brayton cycle, a Rankine cycle, a Kalina cycle, an ejector refrigeration cycle, and a multi-effect desalination unit	Gasification	Power, freshwater, and cooling	77.49 %	(Safder et al., 2021)
Paper	a biomass gasification process, an ejector refrigeration loop, a proton exchange membrane electrolyzer, and a dual organic Rankine cycle with several working fluids (R600-R290)	Gasification	Syngas, power, refrigeration effect, heating load, hydrogen, and oxygen	67.64 %	(Boyaghchi et al., 2018)
Municipal solid waste	a syngas-fuelled solid oxide fuel cell, double-effect absorption chiller, a thermoelectric generator unit	Gasification	Cooling, heating, electricity, and hydrogen/synthetic methane	62.8 %	(Habibollahzade et al., 2021b)
Demolition wood	biomass gasifier unit, gas turbine cycle, Kalina cycle, reverse osmosis unit, proton exchange membrane electrolyzer, absorption cooling cycle, dryer and heat pump	Gasification	Cooling, hydrogen, heating, drying, hot water, and power	59.26 %	(Yilmaz et al., 2019)
Agro-wastes	solid oxide fuel cell stack, gas turbine, steam turbine, gasification and digestion subsystems, organic Rankine and absorption refrigeration cycles	Gasification & Anaerobic digestion	Electrical energy and refrigeration	58.46 %	(Ogorure et al., 2018)
Various waste materials	waste material gasification, Brayton cycle, Stirling engine cycle, single effect absorption cooling system, and hydrogen production, and liquefaction cycle	Gasification	Hydrogen, power, heating-cooling, and hot water	58.15 %	(Yuksel et al., 2019)
Municipal waste	gasification, solid oxide fuel cell, gas turbine, steam turbine, organic Rankine cycle, and absorption refrigeration cycles	Gasification	Power	55.5 %	(Owebor et al., 2019)
Sawdust wood	biomass gasification, Brayton cycle, Kalina cycle, organic Rankine cycle, cascade refrigeration plant, drying system, hydrogen generation with copper–chlorine thermochemical process, and hydrogen liquefaction process	Gasification	Electrical energy, hydrogen, heating, cooling, drying, and hot water	53.59 %	(Onder et al., 2020)
Olive pits	Solid oxide fuel cell, distillation process, Rankine cycle, organic Rankine cycle having an ejector refrigeration process, and hydrogen production and compression	Gasification	Electricity, hydrogen, fresh and hot water, heating, and cooling	52.83 %	(Yuksel et al., 2020)
Algal biomass	a three-step V-Cl thermochemical cycle, a Brayton power generation cycle and a biomass gasification unit fed by *Cladophora glomerata* macroalgae as a marine biomass	Gasification	Green hydrogen and power	52.6 %	(Safari and Dincer, 2022)

development. The present work aims to review articles in the field of biomass-based systems that have been studied recently. The number of studies in this field is numerous; the present work has only investigated systems that provide energy from only one source, i.e., biomass. Systems that have hybrid energy sources are not reviewed in the present article. Classification of systems is employed according to the biomass conversion method and the studies related to the two methods of anaerobic digestion and gasification, as the most widely used methods have been discussed and investigated. The most important results are as follows:

- Generally, due to the high energy content of methane, with an increase in the quality of biogas, its heating value increases; hence the overall energy and exergy efficiency and also the flow rate of the output products of the system increases.

Table 16
Summary of systems with maximum energy and exergy efficiency.

Biomass	Devices	Conversion method	Outputs	η	ψ	Ref.
Sugarcane bagasse	a bagasse-biomass based gasifier-Brayton cycle, a Rankine cycle, a Kalina cycle, an ejector refrigeration cycle, and a multi-effect desalination unit	Gasification	Power, freshwater, and cooling	92.10 %	77.49 %	(Safder et al., 2021)
Paper	a biomass gasification process, an ejector refrigeration loop, a proton exchange membrane electrolyzer, and a dual organic Rankine cycle with several working fluids (R600-R290)	Gasification	Syngas, power, refrigeration effect, heating load, hydrogen, and oxygen	79.35 %	67.64 %	(Boyaghchi et al., 2018)

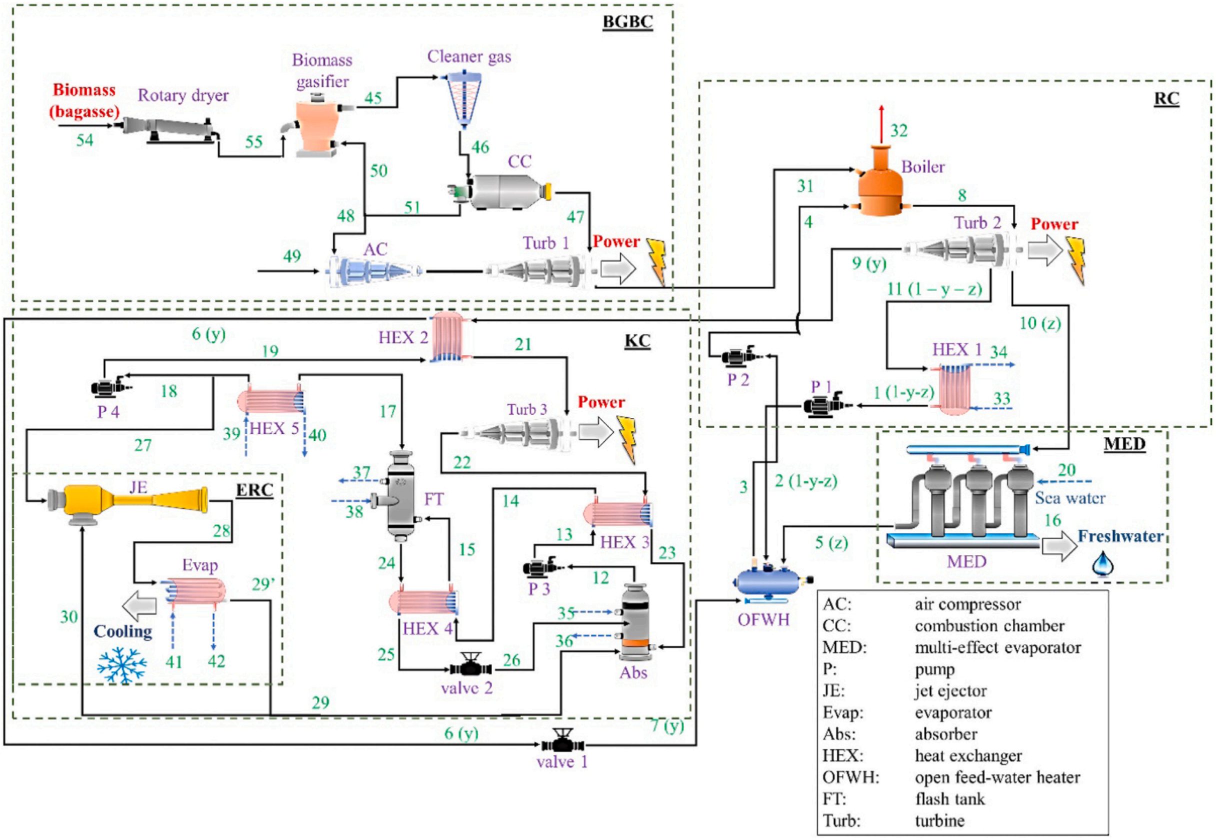

Fig. 24. The schematic of a system with high energy and exergy efficiency presented by Safder et al. (adapted from Safder et al. (2021)).

- In general, adding more biomass into the cycle improves energy efficiency, because more input biomass means more input enthalpy; if input enthalpy to the cycle increases, the input and then output energy will be enhanced. Consequently, increasing useful output products also improves exergy efficiency.
- An increase in the moisture content of biomass generally causes a decrease in the net output work and exergy efficiency of the systems because, with the increase in biomass moisture, its lower heating value decreases. Hence, the net output power from the turbines decreases.
- In biomass gasification-based systems, in general, the system's efficiency is directly related to the temperature of the gasifier. An increase in the temperature of the gasifier causes an increase in the heating value of the produced syngas, so the thermal input energy to the cycle enhances, then the plant reaches a higher temperature, and therefore the waste heat enters the subsystems with a higher enthalpy rate; as a result, the production rate of valuable products of the system and its efficiency increase.
- It seems that the use of the anaerobic digestion method is more effective in improving energy efficiency than exergy efficiency. The use of this method in systems has increased energy efficiency, while in systems with high exergy efficiency, gasification is the most used method.
- The energy and exergy efficiency of the most effective system (from both energy and exergy viewpoints) are 92.10 % and 77.49 %, respectively. This system consists of a gasifier, Brayton cycle, Rankin cycle, Kalina cycle, ejector refrigeration cycle, and a multi-effect desalination unit that has been developed to produce freshwater, power, and cooling.
- In the biomass gasification-based polygeneration systems, the largest share of exergy destruction among the components belongs to the gasifier. More studies are needed to provide effective solutions.
- The use of municipal sewage sludge as input biomass feedstock is less used in articles. Considering that the wastewater disposal method is of particular importance and the wastewater discharge into the seas in some areas has seriously damaged the environment and the ecosystem of the region, and has also neglected a potential source of energy, the design of suitable systems for the use of municipal wastewater is a topic that can attract more attention of researchers in the future.
- The type of material used as an agent in gasifiers can affect system's performance. Choosing the right material should be done according

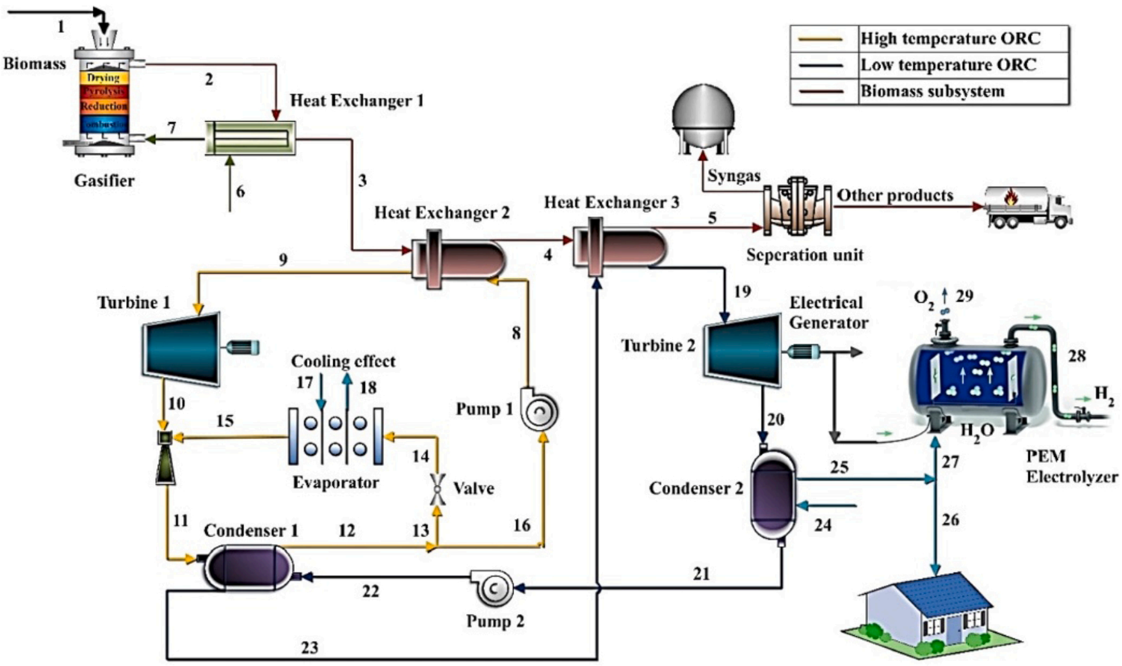

Fig. 25. The schematic of a system with high energy and exergy efficiency presented by Boyaghchi et al. (adapted from Boyaghchi et al. (2018)).

to the criteria considered by the designers. The use of CO_2, which has been investigated in recent studies, is a suitable alternative that can also help to reduce its pollution effects.

- Tar, as the most common pollutant in syngas, is one of the factors that has hindered further commercial progress in gasification. Therefore, it is necessary to conduct more comprehensive studies in this field. Due to its high ability to condense and polymerize, this substance often leads to corrosion and the formation of solid particles and causes damage to devices. The type of gasifiers and agents used in the process can also affect tar formation. Using oxygen as an agent can reduce tar content, while using steam causes more tar production. Moreover, the type of reactor has an important impact on generating this pollutant, in a way that fluidized bed gasifiers reduce the amount of tar production, tar production in entrained flow reactors is zero, and plasma gasifiers are able to destroy tars strongly.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

⟨https://www.eea.europa.eu/help/glossary/eea-glossary/biomass⟩ (Accessed).

Adebayo, V., Abid, M., Adedeji, M., Hussain Ratlamwala, T.A., 2022. Energy, exergy and exergo-environmental impact assessment of a solid oxide fuel cell coupled with absorption chiller & cascaded closed loop ORC for multi-generation. Int. J. Hydrog. Energy 47 (5), 3248–3265. https://doi.org/10.1016/j.ijhydene.2021.02.222.

Aghbashlo, M., et al., 2021. Exergoenvironmental analysis of bioenergy systems: a comprehensive review. Renew. Sustain. Energy Rev. 149, 111399 https://doi.org/10.1016/j.rser.2021.111399.

Al Asfar, J., et al., 2020. Thermodynamic analysis of a biomass-fired lab-scale power plant. Energy 194, 116843. https://doi.org/10.1016/j.energy.2019.116843.

Asadullah, M., 2014. Barriers of commercial power generation using biomass gasification gas: a review. Renew. Sustain. Energy Rev. 29, 201–215. https://doi.org/10.1016/j.rser.2013.08.074.

Auracher, H., 1996. In: Bejan, A., Tsatsaronis, G., Moran, M. (Eds.), Thermal Design and Optimization. John Wiley & Sons, Inc., Hoboken, NJ.

Balafkandeh, S., Zare, V., Gholamian, E., 2019. Multi-objective optimization of a tri-generation system based on biomass gasification/digestion combined with S-CO_2 cycle and absorption chiller. Energy Convers. Manag. 200, 112057 https://doi.org/10.1016/j.enconman.2019.112057.

Bamisile, O., et al., 2020. A biomass-integrated comprehensive energy system: thermodynamics assessment and performance comparison of sugarcane bagasse and rice husk as input source. Energy Sources, Part A Recovery, Util., Environ. Eff. 1–18. https://doi.org/10.1080/15567036.2020.1824037.

Bamisile, O., Huang, Q., Anane, P.O.K., Dagbasi, M., 2019. Performance analyses of a renewable energy powered system for trigeneration. Sustainability 11 (21). https://doi.org/10.3390/su11216006.

Behzadi, A., Arabkoohsar, A., Gholamian, E., 2020. Multi-criteria optimization of a biomass-fired proton exchange membrane fuel cell integrated with organic rankine cycle/thermoelectric generator using different gasification agents. Energy 201, 117640. https://doi.org/10.1016/j.energy.2020.117640.

Behzadi, A., Gholamian, E., Houshfar, E., Habibollahzade, A., 2018a. Multi-objective optimization and exergoeconomic analysis of waste heat recovery from Tehran's waste-to-energy plant integrated with an ORC unit. Energy 160, 1055–1068. https://doi.org/10.1016/j.energy.2018.07.074.

Behzadi, A., Habibollahzade, A., Zare, V., Ashjaee, M., 2019. Multi-objective optimization of a hybrid biomass-based SOFC/GT/double effect absorption chiller/RO desalination system with CO_2 recycle. Energy Convers. Manag. 181, 302–318. https://doi.org/10.1016/j.enconman.2018.11.053.

Behzadi, A., Houshfar, E., Gholamian, E., Ashjaee, M., Habibollahzade, A., 2018b. Multi-criteria optimization and comparative performance analysis of a power plant fed by municipal solid waste using a gasifier or digester. Energy Convers. Manag. 171, 863–878. https://doi.org/10.1016/j.enconman.2018.06.014.

Boyaghchi, F.A., Chavoshi, M., Sabeti, V., 2018. Multi-generation system incorporated with PEM electrolyzer and dual ORC based on biomass gasification waste heat recovery: exergetic, economic and environmental impact optimizations. Energy 145, 38–51. https://doi.org/10.1016/j.energy.2017.12.118.

Buentello-Montoya, D., Zhang, X., 2019. An energy and exergy analysis of biomass gasification integrated with a char-catalytic tar reforming system. Energy Fuels 33 (9), 8746–8757. https://doi.org/10.1021/acs.energyfuels.9b01808.

Calise, F., de Notaristefani di Vastogirardi, G., Dentice d'Accadia, M., Vicidomini, M., 2018. Simulation of polygeneration systems. Energy 163, 290–337. https://doi.org/10.1016/j.energy.2018.08.052.

Cao, Y., et al., 2021a. Multi-objective bat optimization for a biomass gasifier integrated energy system based on 4E analyses. Appl. Therm. Eng. 196, 117339 https://doi.org/10.1016/j.applthermaleng.2021.117339.

Cao, Y., Ehyaei, M.A., 2021. Energy, exergy, economic, and exergoenvironmental (4E) analyses of new configuration ammonia–water solution cycle driven by biomass to produce power and cooling. Energy Sources, Part A Recovery Util. Environ. Eff. 1–19. https://doi.org/10.1080/15567036.2021.1998254.

Cao, Y., Alsharif, S., Attia, E.-A., Shamseldin, M.A., Ibrahim, B.F., 2022a. A conceptual process design towards CO_2 emission reduction by integration of solar-based hydrogen production and injection into biomass-derived solid oxide fuel cell. Process Saf. Environ. Prot. 164, 164–176. https://doi.org/10.1016/j.psep.2022.05.050.

Cao, Y., Bani Hani, E.H., Mansir, I.B., safarzadeh, M., 2022b. Design analysis and tri-objective optimization of a novel integrated energy system based on two methods for hydrogen production: by using power or waste heat. Int. J. Hydrog. Energy 47 (62), 26574–26588. https://doi.org/10.1016/j.ijhydene.2021.09.257.

Cao, Y., Dhahad, H.A., Hussen, H.M., Anqi, A.E., Farouk, N., Issakhov, A., 2022c. Development and tri-objective optimization of a novel biomass to power and hydrogen plant: a comparison of fueling with biomass gasification or biomass digestion. Energy 238, 122010. https://doi.org/10.1016/j.energy.2021.122010.

Cao, Y., Mihardjo, L.W.W., Dahari, M., Tlili, I., 2021b. Waste heat from a biomass fueled gas turbine for power generation via an ORC or compressor inlet cooling via an absorption refrigeration cycle: a thermoeconomic comparison. Appl. Therm. Eng. 182, 116117 https://doi.org/10.1016/j.applthermaleng.2020.116117.

Cartmell, E., et al., 2006. Biosolids a fuel or a waste? An integrated appraisal of five co-combustion scenarios with policy analysis. Environ. Sci. Technol. 40 (3), 649–658. https://doi.org/10.1021/es052181g.

Chattopadhyay, S., Ghosh, S., 2018. Combined energetic and exergetic assessment of a biomass-based integrated power and refrigeration plant. J. Braz. Soc. Mech. Sci. Eng. 40 (3), 134. https://doi.org/10.1007/s40430-018-1060-5.

Chen, Y., Niroumandi, H., Duan, Y., 2021. Thermodynamic and economic analyses of a syngas-fueled high-temperature fuel cell with recycling processes in novel electricity and freshwater cogeneration plant. Energy 235, 121313. https://doi.org/10.1016/j.energy.2021.121313.

Cheng, C., Cherian, J., Sial, M.S., Zaman, U., Niroumandi, H., 2021. Performance assessment of a novel biomass-based solid oxide fuel cell power generation cycle; economic analysis and optimization. Energy 224, 120134. https://doi.org/10.1016/j.energy.2021.120134.

Cho, H., Smith, A.D., Mago, P., 2014. Combined cooling, heating and power: a review of performance improvement and optimization. Appl. Energy 136, 168–185. https://doi.org/10.1016/j.apenergy.2014.08.107.

Cotana, F., Coccia, V., Cavalaglio, G., Barbanera, M., Petrozzi, A., 2022. Chapter 5 - Biomass-based systems. In: Calise, F., Dentice D'Accadia, M., Vanoli, L., Vicidomini, M. (Eds.), Polygeneration Systems. Academic Press, pp. 137–192.

Dincer, I., Acar, C., 2015. A review on clean energy solutions for better sustainability. Int. J. Energy Res. 39 (5), 585–606. https://doi.org/10.1002/er.3329.

Dincer, I., Acar, C., 2018. Chapter 1.1 - potential energy solutions for better sustainability. In: Dincer, I., Colpan, C.O., Kizilkan, O. (Eds.), Exergetic, Energetic and Environmental Dimensions. Academic Press, pp. 3–37.

Ebrahimi, A., Ghorbani, B., Ziabasharhagh, M., Rahimi, M.J., 2021. Biomass gasification process integration with Stirling engine, solid oxide fuel cell, and multi-effect distillation. J. Therm. Anal. Calorim. 145 (3), 1283–1302. https://doi.org/10.1007/s10973-020-10314-9.

Fakhari, I., Behzadi, A., Gholamian, E., Ahmadi, P., Arabkoohsar, A., 2021. Design and tri-objective optimization of a hybrid efficient energy system for tri-generation, based on PEM fuel cell and MED using syngas as a fuel. J. Clean. Prod. 290, 125205 https://doi.org/10.1016/j.jclepro.2020.125205.

Farajollahi, A., Hejazirad, S.A., Rostami, M., 2022. Thermodynamic modeling of a power and hydrogen generation system driven by municipal solid waste gasification. Environ., Dev. Sustain. 24 (4), 5887–5916. https://doi.org/10.1007/s10668-021-01690-9.

Gao, Z., Miao, J., Zhao, J., Mesri, M., 2021. Comprehensive economic analysis and multi-objective optimization of an integrated gasification power generation cycle. Process Saf. Environ. Prot. 155, 61–79. https://doi.org/10.1016/j.psep.2021.09.007.

Ghaffarpour, Z., Mahmoudi, M., Mosaffa, A.H., Garousi Farshi, L., 2018. Thermoeconomic assessment of a novel integrated biomass based power generation system including gas turbine cycle, solid oxide fuel cell and Rankine cycle. Energy Convers. Manag. 161, 1–12. https://doi.org/10.1016/j.enconman.2018.01.071.

Ghiat, I., AlNouss, A., McKay, G., Al-Ansari, T., 2020. Biomass-based integrated gasification combined cycle with post-combustion CO_2 recovery by potassium carbonate: techno-economic and environmental analysis. Comput. Chem. Eng. 135, 106758 https://doi.org/10.1016/j.compchemeng.2020.106758.

Gholamian, E., Hanafizadeh, P., Habibollahzade, A., Ahmadi, P., 2018. Evolutionary based multi-criteria optimization of an integrated energy system with SOFC, gas turbine, and hydrogen production via electrolysis. Int. J. Hydrog. Energy 43 (33), 16201–16214. https://doi.org/10.1016/j.ijhydene.2018.06.130.

Guo, S., Liu, Q., Sun, J., Jin, H., 2018. A review on the utilization of hybrid renewable energy. Renew. Sustain. Energy Rev. 91, 1121–1147. https://doi.org/10.1016/j.rser.2018.04.105.

Habibollahzade, A., Ahmadi, P., Rosen, M.A., 2021b. Biomass gasification using various gasification agents: optimum feedstock selection, detailed numerical analyses and tri-objective grey wolf optimization. J. Clean. Prod. 284, 124718 https://doi.org/10.1016/j.jclepro.2020.124718.

Habibollahzade, A., Gholamian, E., Houshfar, E., Behzadi, A., 2018. Multi-objective optimization of biomass-based solid oxide fuel cell integrated with Stirling engine and electrolyzer. Energy Convers. Manag. 171, 1116–1133. https://doi.org/10.1016/j.enconman.2018.06.061.

Habibollahzade, A., Mehrabadi, Z.K., Houshfar, E., 2021a. Exergoeconomic and environmental optimisations of multigeneration biomass-based solid oxide fuel cell systems with reduced CO_2 emissions. Int. J. Energy Res. 45 (7), 10450–10477. https://doi.org/10.1002/er.6532.

Hamrang, F., Shokri, A., Mahmoudi, S.M.S., Ehghaghi, B., Rosen, M.A., 2020. Performance analysis of a new electricity and freshwater production system based on an integrated gasification combined cycle and multi-effect desalination. Sustainability 12 (19). https://doi.org/10.3390/su12197996.

Hosseinpour, J., Chitsaz, A., Liu, L., Gao, Y., 2020. Simulation of eco-friendly and affordable energy production via solid oxide fuel cell integrated with biomass gasification plant using various gasification agents. Renew. Energy 145, 757–771. https://doi.org/10.1016/j.renene.2019.06.033.

Houshfar, E., 2020. Thermodynamic analysis and multi-criteria optimization of a waste-to-energy plant integrated with thermoelectric generator. Energy Convers. Manag. 205, 112207 https://doi.org/10.1016/j.enconman.2019.112207.

Ifaei, P., Charmchi, A.S.T., Vilela, P., Safder, U., Yoo, C., 2022. A new utility-free circular integration approach for optimal multigeneration from biowaste streams. Energy Convers. Manag. 254, 115269 https://doi.org/10.1016/j.enconman.2022.115269.

Ishaq, H., Dincer, I., 2020. A new energy system based on biomass gasification for hydrogen and power production. Energy Rep. 6, 771–781. https://doi.org/10.1016/j.egyr.2020.02.019.

Ishaq, H., Dincer, I., 2021a. A novel biomass gasification based cascaded hydrogen and ammonia synthesis system using Stoichiometric and Gibbs reactors. Biomass Bioenergy 145, 105929. https://doi.org/10.1016/j.biombioe.2020.105929.

Ishaq, H., Dincer, I., 2021b. An efficient energy utilization of biomass energy-based system for renewable hydrogen production and storage. J. Energy Resour. Technol. 144 (1) https://doi.org/10.1115/1.4050875.

Ishaq, H., Islam, S., Dincer, I., Yilbas, B.S., 2020. Development and performance investigation of a biomass gasification based integrated system with thermoelectric generators. J. Clean. Prod. 256, 120625 https://doi.org/10.1016/j.jclepro.2020.120625.

Jabari, F., Mohammadi-ivatloo, B., Bannae-Sharifian, M.-B., Ghaebi, H., 2018. Design and performance investigation of a biogas fueled combined cooling and power generation system. Energy Convers. Manag. 169, 371–382. https://doi.org/10.1016/j.enconman.2018.05.026.

Jabari, F., Mohammadi-ivatloo, B., Ghaebi, H., Bannae-sharifian, M.-B., 2019. Biogas fueled combined cooling, desalinated water and power generation systems. J. Clean. Prod. 219, 906–924. https://doi.org/10.1016/j.jclepro.2019.01.272.

Ji-chao, Y., Sobhani, B., 2021. Integration of biomass gasification with a supercritical CO_2 and Kalina cycles in a combined heating and power system: a thermodynamic and exergoeconomic analysis. Energy 222, 119980. https://doi.org/10.1016/j.energy.2021.119980.

Karimi, M.H., Chitgar, N., Emadi, M.A., Ahmadi, P., Rosen, M.A., 2020. Performance assessment and optimization of a biomass-based solid oxide fuel cell and micro gas turbine system integrated with an organic Rankine cycle. Int. J. Hydrog. Energy 45 (11), 6262–6277. https://doi.org/10.1016/j.ijhydene.2019.12.143.

Karl, J., Pröll, T., 2018. Steam gasification of biomass in dual fluidized bed gasifiers: a review. Renew. Sustain. Energy Rev. 98, 64–78. https://doi.org/10.1016/j.rser.2018.09.010.

Kasaeian, A., Bellos, E., Shamaeizadeh, A., Tzivanidis, C., 2020. Solar-driven polygeneration systems: recent progress and outlook. Appl. Energy 264, 114764. https://doi.org/10.1016/j.apenergy.2020.114764.

Khaliq, A., Dincer, I., 2011. Energetic and exergetic performance analyses of a combined heat and power plant with absorption inlet cooling and evaporative aftercooling. Energy 36 (5), 2662–2670. https://doi.org/10.1016/j.energy.2011.02.007.

Khanh Nguyen, V., et al., 2021. Review on pretreatment techniques to improve anaerobic digestion of sewage sludge. Fuel 285, 119105. https://doi.org/10.1016/j.fuel.2020.119105.

Khanmohammadi, S., Atashkari, K., 2018. Modeling and multi-objective optimization of a novel biomass feed polygeneration system integrated with multi effect desalination unit. Therm. Sci. Eng. Prog. 8, 269–283. https://doi.org/10.1016/j.tsep.2018.08.003.

Khanmohammadi, S., Musharavati, F., Tariq, R., 2022. A framework of data modeling and artificial intelligence for environmental-friendly energy system: application of Kalina cycle improved with fuel cell and thermoelectric module. Process Saf. Environ. Prot. 164, 499–516. https://doi.org/10.1016/j.psep.2022.06.029.

Khanmohammadi, S., Saadat-Targhi, M., Al-Rashed, A.A.A.A., Afrand, M., 2019. Thermodynamic and economic analyses and multi-objective optimization of harvesting waste heat from a biomass gasifier integrated system by thermoelectric generator. Energy Convers. Manag. 195, 1022–1034. https://doi.org/10.1016/j.enconman.2019.05.075.

Köse, Ö., Koç, Y., Yağlı, H., 2022. Is Kalina cycle or organic Rankine cycle for industrial waste heat recovery applications? A detailed performance, economic and environment based comprehensive analysis. Process Saf. Environ. Prot. 163, 421–437. https://doi.org/10.1016/j.psep.2022.05.041.

Lak Kamari, M., Maleki, A., Alhuyi Nazari, M., Sadeghi, M., Rosen, M.A., Pourfayaz, F., 2021. Assessment of a biomass-based polygeneration plant for combined power, heat, bioethanol and biogas. Appl. Therm. Eng. 198, 117425 https://doi.org/10.1016/j.applthermaleng.2021.117425.

Li, S., Zhu, L., He, Y., Fan, J., Lv, L., 2020. Thermodynamic evaluation of CCHP system based on biomass gasification by exploring the feasibility of using CO_2 as gasification agent. Sustain. Energy Technol. Assess. 42, 100867 https://doi.org/10.1016/j.seta.2020.100867.

Li, Y., Li, Y., Zhang, X., Wang, C., Li, X., Ma, L., 2021. Exergy analysis of renewable light olefin production system via biomass gasification and methanol synthesis. Int. J. Hydrog. Energy 46 (5), 3669–3683. https://doi.org/10.1016/j.ijhydene.2020.10.213.

Li, Y., Ye, M., Tan, F., Wang, C., Long, J., 2022. Exergy analysis of alternative configurations of biomass-based light olefin production system with a combined-cycle scheme via methanol intermediate. Energies 15 (2). https://doi.org/10.3390/en15020404.

Liew, C.S., et al., 2022. A review on recent disposal of hazardous sewage sludge via anaerobic digestion and novel composting. J. Hazard. Mater. 423, 126995 https://doi.org/10.1016/j.jhazmat.2021.126995.

Mehrabadi, Z.K., Boyaghchi, F.A., 2019. Thermodynamic, economic and environmental impact studies on various distillation units integrated with gasification-based multi-generation system: comparative study and optimization. J. Clean. Prod. 241, 118333 https://doi.org/10.1016/j.jclepro.2019.118333.

Mehrabadi, Z.K., Boyaghchi, F.A., 2021. Exergoeconomic and exergoenvironmental analyses and optimization of a new low-CO_2 emission energy system based on gasification-solid oxide fuel cell to produce power and freshwater using various fuels. Sustain. Prod. Consum. 26, 782–804. https://doi.org/10.1016/j.spc.2020.12.041.

Mehrpooya, M., Khalili, M., Sharifzadeh, M.M.M., 2018. Model development and energy and exergy analysis of the biomass gasification process (Based on the various biomass sources. Renew. Sustain. Energy Rev. 91, 869–887. https://doi.org/10.1016/j.rser.2018.04.076.

Mohammadikhah, F., Javaherdeh, K., Mahmoudimehr, J., 2021. Thermodynamic analysis and multi-objective optimization of a new biomass-driven multi-generation system for zero energy buildings. Energy Syst. 12 (1), 157–180. https://doi.org/10.1007/s12667-020-00379-8.

Moharamian, A., Soltani, S., Rosen, M.A., Mahmoudi, S.M.S., 2018. Exergoeconomic and thermodynamic analyses of an externally fired combined cycle with hydrogen production and injection to the combustion chamber. Int. J. Hydrog. Energy 43 (2), 781–792. https://doi.org/10.1016/j.ijhydene.2017.11.136.

Mojaver, P., Khalilarya, S., Chitsaz, A., 2020. Multi-objective optimization and decision analysis of a system based on biomass fueled SOFC using couple method of entropy/VIKOR. Energy Convers. Manag. 203, 112260 https://doi.org/10.1016/j.enconman.2019.112260.

Murugan, S., Horák, B., 2016. Tri and polygeneration systems - a review. Renew. Sustain. Energy Rev. 60, 1032–1051. https://doi.org/10.1016/j.rser.2016.01.127.

Musharavati, F., Khoshnevisan, A., Alirahmi, S.M., Ahmadi, P., Khanmohammadi, S., 2022. Multi-objective optimization of a biomass gasification to generate electricity and desalinated water using Grey Wolf Optimizer and artificial neural network. Chemosphere 287, 131980. https://doi.org/10.1016/j.chemosphere.2021.131980.

Ogorure, O.J., Oko, C.O.C., Diemuodeke, E.O., Owebor, K., 2018. Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant. Energy Convers. Manag. 171, 222–240. https://doi.org/10.1016/j.enconman.2018.05.093.

Onder, G., Yilmaz, F., Ozturk, M., 2020. Thermodynamic performance analysis of a copper–chlorine thermochemical cycle and biomass based combined plant for multigeneration. Int. J. Energy Res. 44 (9), 7548–7567. https://doi.org/10.1002/er.5482.

Ong, H.C., Chen, W.-H., Farooq, A., Gan, Y.Y., Lee, K.T., Ashokkumar, V., 2019. Catalytic thermochemical conversion of biomass for biofuel production: a comprehensive review. Renew. Sustain. Energy Rev. 113, 109266 https://doi.org/10.1016/j.rser.2019.109266.

Owebor, K., Oko, C.O.C., Diemuodeke, E.O., Ogorure, O.J., 2019. Thermo-environmental and economic analysis of an integrated municipal waste-to-energy solid oxide fuel cell, gas-, steam-, organic fluid- and absorption refrigeration cycle thermal power plants. Appl. Energy 239, 1385–1401. https://doi.org/10.1016/j.apenergy.2019.02.032.

Ozbas, E.E., Aksu, D., Ongen, A., Aydin, M.A., Ozcan, H.K., 2019. Hydrogen production via biomass gasification, and modeling by supervised machine learning algorithms. Int. J. Hydrog. Energy 44 (32), 17260–17268. https://doi.org/10.1016/j.ijhydene.2019.02.108.

Pal, D.B., Singh, A., Bhatnagar, A., 2022. A review on biomass based hydrogen production technologies. Int. J. Hydrog. Energy 47 (3), 1461–1480. https://doi.org/10.1016/j.ijhydene.2021.10.124.

Rahimi, M.J., Ghorbani, B., Amidpour, M., Hamedi, M.H., 2021. Configuration optimization of a multi-generation plant based on biomass gasification. Energy 227, 120457. https://doi.org/10.1016/j.energy.2021.120457.

Rajabi, M., Mehrpooya, M., Haibo, Z., Huang, Z., 2019. Chemical looping technology in CHP (combined heat and power) and CCHP (combined cooling heating and power) systems: a critical review. Appl. Energy 253, 113544. https://doi.org/10.1016/j.apenergy.2019.113544.

Rashidi, H., Khorshidi, J., 2018. Exergy analysis and multiobjective optimization of a biomass gasification based multigeneration system. Int. J. Hydrog. Energy 43 (5), 2631–2644. https://doi.org/10.1016/j.ijhydene.2017.12.073.

Razmi, A.R., Heydari Afshar, H., Pourahmadiyan, A., Torabi, M., 2021. Investigation of a combined heat and power (CHP) system based on biomass and compressed air energy storage (CAES. Sustain. Energy Technol. Assess. 46, 101253 https://doi.org/10.1016/j.seta.2021.101253.

Rong, A., Lahdelma, R., 2016. Role of polygeneration in sustainable energy system development challenges and opportunities from optimization viewpoints. Renew. Sustain. Energy Rev. 53, 363–372. https://doi.org/10.1016/j.rser.2015.08.060.

Roy, D., 2020. Performance evaluation of a novel biomass-based hybrid energy system employing optimisation and multi-criteria decision-making techniques. Sustain. Energy Technol. Assess. 42, 100861 https://doi.org/10.1016/j.seta.2020.100861.

Roy, D., Samanta, S., Ghosh, S., 2019. Techno-economic and environmental analyses of a biomass based system employing solid oxide fuel cell, externally fired gas turbine and organic Rankine cycle. J. Clean. Prod. 225, 36–57. https://doi.org/10.1016/j.jclepro.2019.03.261.

Roy, D., Samanta, S., Ghosh, S., 2020a. Performance assessment of a biomass-fuelled distributed hybrid energy system integrating molten carbonate fuel cell, externally fired gas turbine and supercritical carbon dioxide cycle. Energy Convers. Manag. 211, 112740 https://doi.org/10.1016/j.enconman.2020.112740.

Roy, D., Samanta, S., Ghosh, S., 2020b. Performance optimization through response surface methodology of an integrated biomass gasification based combined heat and power plant employing solid oxide fuel cell and externally fired gas turbine. Energy Convers. Manag. 222, 113182 https://doi.org/10.1016/j.enconman.2020.113182.

Ruiz, J.A., Juárez, M.C., Morales, M.P., Muñoz, P., Mendívil, M.A., 2013. Biomass gasification for electricity generation: review of current technology barriers. Renew. Sustain. Energy Rev. 18, 174–183. https://doi.org/10.1016/j.rser.2012.10.021.

Sadeghi, M., Mehr, A.S., Zar, M., Santarelli, M., 2018. Multi-objective optimization of a novel syngas fed SOFC power plant using a downdraft gasifier. Energy 148, 16–31. https://doi.org/10.1016/j.energy.2018.01.114.

Sadi, M., Chakravarty, K.H., Behzadi, A., Arabkoohsar, A., 2021. Techno-economic-environmental investigation of various biomass types and innovative biomass-firing technologies for cost-effective cooling in India. Energy 219, 119561. https://doi.org/10.1016/j.energy.2020.119561.

Safari, F., Dincer, I., 2019. Development and analysis of a novel biomass-based integrated system for multigeneration with hydrogen production. Int. J. Hydrog. Energy 44 (7), 3511–3526. https://doi.org/10.1016/j.ijhydene.2018.12.101.

Safari, F., Dincer, I., 2022. Assessment and multi-objective optimization of a vanadium-chlorine thermochemical cycle integrated with algal biomass gasification for hydrogen and power production. Energy Convers. Manag. 253, 115132 https://doi.org/10.1016/j.enconman.2021.115132.

Safarian, S., Unnthorsson, R., Richter, C., 2022. Hydrogen production via biomass gasification: simulation and performance analysis under different gasifying agents. Biofuels 13 (6), 717–726. https://doi.org/10.1080/17597269.2021.1894781.

Safder, U., Nguyen, H.-T., Ifaei, P., Yoo, C., 2021. Energetic, economic, exergetic, and exergorisk (4E) analyses of a novel multi-generation energy system assisted with bagasse-biomass gasifier and multi-effect desalination unit. Energy 219, 119638. https://doi.org/10.1016/j.energy.2020.119638.

Saini, P., Singh, J., Sarkar, J., 2021. Novel combined desalination, heating and power system: energy, exergy, economic and environmental assessments. Renew. Sustain. Energy Rev. 151, 111612 https://doi.org/10.1016/j.rser.2021.111612.

Salehi, A., Mousavi, S.M., Fasihfar, A., Ravanbakhsh, M., 2019. Energy, exergy, and environmental (3E) assessments of an integrated molten carbonate fuel cell (MCFC), Stirling engine and organic Rankine cycle (ORC) cogeneration system fed by a biomass-fueled gasifier. Int. J. Hydrog. Energy 44 (59), 31488–31505. https://doi.org/10.1016/j.ijhydene.2019.10.038.

Segurado, R., Pereira, S., Correia, D., Costa, M., 2019. Techno-economic analysis of a trigeneration system based on biomass gasification. Renew. Sustain. Energy Rev. 103, 501–514. https://doi.org/10.1016/j.rser.2019.01.008.

Sevinchan, E., Dincer, I., Lang, H., 2019. Energy and exergy analyses of a biogas driven multigenerational system. Energy 166, 715–723. https://doi.org/10.1016/j.energy.2018.10.085.

Shayan, E., Zare, V., Mirzaee, I., 2018. Hydrogen production from biomass gasification; a theoretical comparison of using different gasification agents. Energy Convers. Manag. 159, 30–41. https://doi.org/10.1016/j.enconman.2017.12.096.

Siddiqui, O., Dincer, I., 2021. Sustainable utilization of agricultural bio-waste for multigeneration of electricity, heating, cooling and freshwater. J. Clean. Prod. 319, 128540 https://doi.org/10.1016/j.jclepro.2021.128540.

Sikarwar, S.S., Surywanshi, G.D., Patnaikuni, V.S., Kakunuri, M., Vooradi, R., 2020. Chemical looping combustion integrated Organic Rankine Cycled biomass-fired power plant – energy and exergy analyses. Renew. Energy 155, 931–949. https://doi.org/10.1016/j.renene.2020.03.114.

Soltani, S., 2019. Modified exergy and exergoeconomic analyses of a biomass post fired hydrogen production combined cycle. Renew. Energy 135, 1466–1480. https://doi.org/10.1016/j.renene.2018.09.074.

Soltanian, S., et al., 2022. Exergetic sustainability analysis of municipal solid waste treatment systems: a systematic critical review. Renew. Sustain. Energy Rev. 156, 111975 https://doi.org/10.1016/j.rser.2021.111975.

Sorgulu, F., Dincer, I., 2021. Development and assessment of a biomass-based cogeneration system with desalination. Appl. Therm. Eng. 185, 116432 https://doi.org/10.1016/j.applthermaleng.2020.116432.

Sotoodeh, A.F., Ahmadi, F., Ghaffarpour, Z., Ebadollahi, M., Nasrollahi, H., Amidpour, M., 2022. Performance analyses of a waste-to-energy multigeneration system incorporated with thermoelectric generators. Sustain. Energy Technol. Assess. 49, 101649 https://doi.org/10.1016/j.seta.2021.101649.

Taheri, M.H., Khani, L., Mohammadpourfard, M., Aminfar, H., 2021. Multi-objective optimization of a novel biomass-based multigeneration system consisting of liquid natural gas open cycle and proton exchange membrane electrolyzer. Int. J. Energy Res. 45 (11), 16806–16823. https://doi.org/10.1002/er.6931. ⟨https://doi.org/10.1002/er.6931⟩, 2021/09/01.

Teng, S., Hamrang, F., Ashraf Talesh, S.S., 2021. Economic performance assessment of a novel combined power generation cycle. Energy 231, 121092. https://doi.org/10.1016/j.energy.2021.121092.

Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C.Ö., Ayol, A., 2022. Biomass gasification for sustainable energy production: a review. Int. J. Hydrog. Energy 47 (34), 15419–15433. https://doi.org/10.1016/j.ijhydene.2022.02.158.

Tsatsaronis, G., 2007. Definitions and nomenclature in exergy analysis and exergoeconomics. Energy 32 (4), 249–253. https://doi.org/10.1016/j.energy.2006.07.002.

Villarini, M., Marcantonio, V., Colantoni, A., Bocci, E., 2019. Sensitivity analysis of different parameters on the performance of a CHP internal combustion engine system fed by a biomass waste gasifier. Energies 12 (4). https://doi.org/10.3390/en12040688.

Wegener, M., Malmquist, A., Isalgué, A., Martin, A., 2018. Biomass-fired combined cooling, heating and power for small scale applications – a review. Renew. Sustain. Energy Rev. 96, 392–410. https://doi.org/10.1016/j.rser.2018.07.044.

Xiang, Y., Zhou, J., Lin, B., Xue, X., Tian, X., Luo, Z., 2015. Exergetic evaluation of renewable light olefins production from biomass via synthetic methanol. Appl. Energy 157, 499–507. https://doi.org/10.1016/j.apenergy.2015.05.039.

Xu, Y.-P., et al., 2022. Optimization of a biomass-driven Rankine cycle integrated with multi-effect desalination, and solid oxide electrolyzer for power, hydrogen, and freshwater production. Desalination 525, 115486. https://doi.org/10.1016/j.desal.2021.115486.

Xue, X., et al., 2022. Performance evaluation of a conceptual compressed air energy storage system coupled with a biomass integrated gasification combined cycle. Energy 247, 123442. https://doi.org/10.1016/j.energy.2022.123442.

Yan, L., Cao, Y., He, B., 2019. Energy, exergy and economic analyses of a novel biomass fueled power plant with carbon capture and sequestration. Sci. Total Environ. 690, 812–820. https://doi.org/10.1016/j.scitotenv.2019.07.015.

Yilmaz, F., Ozturk, M., Selbas, R., 2019. Development and techno-economic assessment of a new biomass-assisted integrated plant for multigeneration. Energy Convers. Manag. 202, 112154 https://doi.org/10.1016/j.enconman.2019.112154.

Yilmaz, F., Ozturk, M., Selbas, R., 2020. Design and thermodynamic assessment of a biomass gasification plant integrated with Brayton cycle and solid oxide steam electrolyzer for compressed hydrogen production. Int. J. Hydrog. Energy 45 (60), 34620–34636. https://doi.org/10.1016/j.ijhydene.2020.02.174.

Younas, M., Shafique, S., Hafeez, A., Javed, F., Rehman, F., 2022. An overview of hydrogen production: current status, potential, and challenges. Fuel 316, 123317. https://doi.org/10.1016/j.fuel.2022.123317.

Yuksel, Y.E., Ozturk, M., Dincer, I., 2019. Energy and exergy analyses of an integrated system using waste material gasification for hydrogen production and liquefaction. Energy Convers. Manag. 185, 718–729. https://doi.org/10.1016/j.enconman.2019.02.033.

Yuksel, Y.E., Ozturk, M., Dincer, I., 2020. Performance investigation of a combined biomass gasifier-SOFC plant for compressed hydrogen production. Int. J. Hydrog. Energy 45 (60), 34679–34694. https://doi.org/10.1016/j.ijhydene.2020.05.076.

Zaman, S.A., Ghosh, S., 2022. Thermo-economic and environmental performance analyses of a biomass-based carbon negative system integrating externally fired gas turbine and molten carbonate fuel cell. Energy Convers. Manag. X 14, 100187. https://doi.org/10.1016/j.ecmx.2022.100187.

Zare, V., 2020. Role of modeling approach on the results of thermodynamic analysis: concept presentation via thermoeconomic comparison of biomass gasification-fueled open and closed cycle gas turbines. Energy Convers. Manag. 225, 113479 https://doi.org/10.1016/j.enconman.2020.113479.

Zhang, Y., Xu, P., Liang, S., Liu, B., Shuai, Y., Li, B., 2019. Exergy analysis of hydrogen production from steam gasification of biomass: a review. Int. J. Hydrog. Energy 44 (28), 14290–14302. https://doi.org/10.1016/j.ijhydene.2019.02.064.

Zhao, Z., Shi, X., Zhang, M., Ouyang, T., 2022. Multi-scale assessment and multi-objective optimization of a novel solid oxide fuel cell hybrid power system fed by bio-syngas. J. Power Sources 524, 231047. https://doi.org/10.1016/j.jpowsour.2022.231047.