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Bioenergy Generation from Thermochemical Conversion of Lignocellulosic Biomass-based Integrated Renewable Energy Systems

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Abstract

Anthropogenic activities and advancements in industries boost global energy demand and increase fossil fuel consumption, causing several global environmental problems, such as climate change. As a climate change mitigation strategy, the use of renewable energy technologies has gained unprecedented interest. In particular, the thermochemical processing of lignocellulosic biomass integrated with other renewable energy technologies has emerged rapidly. It is critical to select appropriate integrated renewable energy system configurations for sustainable and feasible power generation towards higher environmental benefits. Understanding the possible configurations of thermochemical lignocellulosic biomass processing technologies (gasification, pyrolysis, hydrothermal gasification, or hydrothermal carbonization) integrated with renewable energy technologies (solar thermal, fuel cell, fusion power, or energy storage) is crucial for the further development and propagation of the integrated renewable energy system. Hence, we provide a systematic review of the thermochemical conversion of lignocellulosic biomass integrated with the other renewable energy technologies. Finally, the challenges associated with the implementation of these systems and suggestions for future research on the systems are discussed.

Keywords: biofuels; biorefinery; hybrid energy system; power generation; sustainable energy

1. Introduction

The paradigm shift to a low carbon bioeconomy of renewable bioenergy-based power generation is essential as a long-term strategy for sustainable energy generation to cater to the high energy demand and reduce the dependence on fossil fuels. Biomass is one of the primary energy resources globally, and bioenergy is considered to be a more stable form of renewable energy as compared to, e.g., solar and wind energy which are affected by the intermittent environmental and meteorological conditions [1]. In addition, the bioenergy system has the potential to be carbon neutral and has a higher contribution to employment compared to other renewable energy development [2] and greatly contributes to the mitigation of adverse climate change [3].

Lignocellulosic biomass normally refers to terrestrial plant biomass that comprises cellulose, hemicellulose, and lignin. Lignocellulosic biomass has been considered an alternative to fossil-based products, such as fuels and chemicals, and acknowledged as a valuable renewable energy resource. Global annual production of lignocellulosic biomass was estimated to be approximately 181.5 billion tons [4]. Currently, about 0.2 % of the total land of the world (~ 25 million ha) is used to grow bioenergy feedstocks [5]. Hence, the availability of lignocellulosic biomass is not an important issue for producing bio-based fuels and chemicals that can potentially substitute fossil-based fuels and chemicals, respectively.

Lignocellulosic biomass can be transformed into either gas or liquid fuels through various technologies that can be categorized into physical, thermal, chemical, and biological conversion processes [6-13]. Gasification, pyrolysis, and hydrothermal carbonization are representative of the thermochemical lignocellulosic biomass conversion processes. Their applications are highly associated with the kind of target product (gas, liquid, or solid), the extent of oxidation environment (partial or anaerobic), and the type of feedstock (wet or dry) [14-16]. Thermochemical conversion technologies have also shown great promise for generating electricity from biomass by co-combustion of the biomass with coal in existing power plants [17] and decentralized electricity generation in developing countries [18-21]. In addition, electricity generated from biomass through thermochemical conversion processes could help fulfill the renewable portfolio standards enacted in many states of the USA [22].

Single resource-based renewable energy systems are commonly employed to generate power [23, 24]; however, they are often cost-ineffective and unreliable [25]. The intermittent nature of single-resource renewable energy technologies may interrupt continuous energy supply. Integrated renewable energy systems can increase the energy storage capacity, save the cost of power generation, improve the generated-power quality, and enhance the total energy conversion efficiency of power generation, compared to the single resource based-systems for energy generation [26, 27]. Furthermore, the integrated renewable energy systems can allow easy transmission and distribution of clogs, diminish line and transformer accidents, enhance the standard of control during the power generation, and reduce detrimental impacts of the power generation on the environment, thereby increasing the overall reliability of the power generation [28]. The application of variable locally available unutilized resources (e.g., lignocellulosic biomass) in an integrated energy system configuration can help to avoid the intermittence issue of a single-resource renewable energy system (e.g., photovoltaics (PV) and wind power). Thus, integrated systems can offer a greater degree of flexibility in utilizing local renewable resources and have higher potential for local employment than single-source systems [2].

Thermochemical biomass conversion-based integrated renewable energy systems to generate power have received relatively little attention in comparison with single conversion processes [29-31]. Hence, this review aims to support wider practical applications of bioenergy-based renewable energy systems that integrate each of the thermochemical biomass conversion processes (e.g., gasification, pyrolysis, and hydrothermal process) with any other renewable energy resource (e.g., solar thermal energy resource and fuel cells). From this perspective, we provide a systematic overview of the thermochemical conversion process-based hybrid lignocellulosic biomass-to-power systems. Fig. 1 schematically describes the hybrid system configurations dealt with in this review. Finally, the challenges faced by these systems are discussed, and recommendations for future research directions of the systems are offered.

2. Thermochemical conversion processes

2.1. Gasification

Gasification is a process that transforms lignocellulosic biomass into gaseous products containing large fractions of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). This transformation can be achieved at high temperatures (typically more than 700 °C) under precisely controlled air, oxygen, and/or steam environments. The resultant gas mixture (gaseous products) transformation is named synthesis gas (syngas) or producer gas, and the syngas itself can be used as a fuel because flammable contents, e.g., H_2 and CO. Notably, the gasification of lignocellulosic biomass has a high potential to enhance the exergy efficiency of a combined heat and power (CHP) system [32]. Furthermore, the lignocellulosic biomass gasification-based heat and power generation can be eco-friendlier than that based on direct combustion of the biomass. For example, electricity generation through gasification of timber leads to a global warming potential of <50 kg CO_2-eq t^{-1}, acidification potential of 55 kg SO_2-eq t^{-1}, and eutrophication potential of 220 kg NO_3-eq t^{-1} which are very much less than those from direct timber combustion (1900 CO_2-eq t^{-1}, 90 SO_2-eq t^{-1}, and 305 kg NO_3-eq t^{-1}), respectively [33].

2.2. Pyrolysis

Pyrolysis, the thermochemical decomposition of carbonaceous substances in the absence of oxygen (thus avoiding combustion) at a temperature of 300–1200 °C [16], has gained increasing attention as a sustainable lignocellulosic biomass conversion process. Recently, pyrolysis has been widely studied to transform lignocellulosic biomass into high-value products (e.g., H_2 [34], commodity chemicals [35], and catalysts [36]). Pyrolysis is an effective process for treating carbonaceous substances in a heterogeneous and complex material/source, such as lignocellulosic biomass [37]. The pyrolysis of lignocellulosic biomass typically results in pyrolytic products in three different phases, namely pyrolytic gas, bio-oil, and char. Pyrolytic gas is a mixture of permanent gases, such as H_2, CO, and CO_2, and light hydrocarbons, such as methane (CH_4), ethane, ethylene, propane, propylene, butane, and butylene [38]. Bio-oil (also called pyrolytic liquid, tar, or biocrude) is a complex mixture of water, organic components (composed mainly of organic acids, alcohol, aldehydes, phenols, and furans), and a small amount of ash [39]. Finally, char is a solid residue remaining after the lignocellulosic biomass pyrolysis, typically used as a solid fuel (a renewable alternative to coal) [40]. All these pyrolytic products are considered renewable energy sources because they can be combusted to generate power. The yield and characteristics of each pyrolytic product are highly associated with the pyrolytic conditions, such as the temperature, heating rate, and feedstock residence time of the pyrolysis [41].

2.3. Hydrothermal conversion

While gasification and pyrolysis require dry biomass as the feedstock, hydrothermal conversion (e.g., hydrothermal gasification and hydrothermal carbonization) is a process of transforming lignocellulosic biomass with a high moisture content (i.e., wet lignocellulosic biomass) into bio-oil and char [42]. In particular, the hydrothermal gasification process processes lignocellulosic biomass in hot compressed water, typically supercritical or subcritical liquid water, at a temperature of 400–600 °C, for several minutes [43]. On the other hand, the hydrothermal carbonization is a process of converting lignocellulosic biomass at a temperature and pressure of 180–280 °C and 2–6 MPa, respectively, for 5–240 min [44]. Hydrothermal conversion of lignocellulosic biomass can produce bio-oil and char having high energy density for efficient energy recovery [45-47]. Recently, a study has shown that the combustion of bio-oil and char derived from lignocellulosic biomass (e.g., bagasse) using the hydrothermal conversion process can offer a 170 % higher electricity export benefit than that offered by conventional direct combustion of the lignocellulosic biomass [48]. Table 1 compares advantages and disadvantages of the three thermochemical conversion processes.

3. Gasification-based integrated systems

This section introduces and discusses the bioenergy-based renewable energy systems integrating gasification of lignocellulosic biomass and other renewable energy technologies (e.g., solar thermal energy, solid oxide fuel cell, anaerobic digestion, and energy storage unit). Table 2 summarizes recent data on lignocellulosic biomass gasification-based integrated renewable energy systems.

3.1. Integrated with solar thermal energy

Concentrated solar thermal energy conversion uses mirrors (or lenses) to concentrate sunlight from a large area onto a receiver (i.e., solar concentrator) [49]. The concentrated sunlight is then used to generate heat for driving a heat engine (e.g., steam turbine) [50] or power a thermochemical process [51]. Concentrated solar thermal energy can be used to meet energy demands (e.g., heat) for lignocellulosic biomass gasification [52-58]. Likewise, a hybrid power generation system using biomass and solar energies was also suggested [59]. This system integrated a biomass gasification process and a concentrated solar thermal energy conversion process through a heat exchanger network (entry 1 in Table 2), as depicted in Fig. 2a. The biomass gasification took place in a bubbling fluidized-bed reactor with the heat received from the concentrated solar thermal energy to produce syngas that was used as fuel for a gas turbine. Excess heat from the gasification was used in a Rankine-cycle steam turbine to generate power. Notably, the temperature and composition of the gasifying agent (e.g., a mixture of oxygen (O_2) and steam) affected the overall efficiency of the integrated system. For example, an increase in the temperature and O_2 fraction in the gasifying agent led to an increased overall efficiency of the integrated system. Furthermore, an increase in the heat input from the concentrated solar thermal energy increased the overall system efficiency until the heat input became dominant compared to the heat of the fluid stream in either the gasification process or gas turbine. However, the biomass gasification/concentrated solar thermal energy integrated systems often suffer from the instability of system operation and require an overcomplicated process control for the system because of the intermittent solar radiation coming on to the system.

The concept of integrating autothermal and solar gasification of lignocellulosic biomass has been proposed to overcome the above-mentioned issue of intermittent solar radiation and continuous syngas production with a high biomass conversion efficiency [60-62]. For example, Li et al. [62] suggested a biomass gasification process under either autothermal or solar modes (Fig. 2b). Their integrated system was developed to continuously produce syngas from biomass, such as redwood (entry 2 in Table 2). The produced syngas was then exploited to drive combined cooling, heat, and power systems. Notably, Li et al. investigated the respective impacts of solar flux inputs and reactant ratios on the syngas production. The investigation showed that an operation for 2 days at the optimum production conditions (minimum steam supply and temperature more than 730 °C) resulted in an increase in the molar flow rates of CO and H_2 in the syngas by ~12 % and 39 %, respectively, increasing the lower heating value

(LHV) of the syngas by up to 52 %. In addition, the primary energy ratio of the integrated system was also increased by ~12 % when the system was operated under simultaneous autothermal/solar modes.

3.2. Integrated with solid oxide fuel cell

A solid oxide fuel cell has a solid oxide (e.g., non-porous metal oxide) or ceramic electrolyte, electrochemically generating electricity by oxidizing a fuel. The solid oxide fuel cells provide high CHP efficiency and have fuel flexibility, high stability, and low emissions as compared to other types of fuel cells [63]. However, the requirement of a high operating temperature (750–1000 °C) for a solid oxide fuel cell is a disadvantage of this fuel cell [64].

There have been efforts to develop systems integrating lignocellulosic biomass gasification and solid oxide fuel cell [65] to achieve high electrical efficiencies. Theoretical studies have shown that the electrical efficiencies of lignocellulosic biomass gasification/solid oxide fuel cell integrated systems could reach 40–42 % [66-69]. However, the gasifying agent affects the performance of the lignocellulosic biomass gasification/solid oxide fuel cell integrated system. For example, the electrical efficiency of this integrated system using air, oxygen-enriched air, and steam as the gasification agent was 28 %, 29 %, and 42 %, respectively [68, 69]. In addition, an electrical efficiency of 42–58 % was achieved for this integrated system when the exhaust from the solid oxide fuel cell was expanded in a gas turbine to generate additional electricity [70-75]. Further, a CHP system consisting of autothermal gasification of lignocellulosic biomass, solid oxide fuel cell, and micro gas-turbine was proposed by Borji et al. [75], which had a maximum electrical efficiency of 42 %. In particular, this efficiency was affected by the air/steam ratio in the gasification, fuel temperature at the inlet of the solid oxide fuel cell, the average current density in the fuel cell, and the fuel utilization factor of the fuel cell. Similarly, Bang-Møller et al. [72] constructed an integrated plant composed of lignocellulosic biomass gasification, solid oxide fuel cell, and micro gas-turbine, which had a power of 290 kW and an electrical efficiency of 58.2 %.

A conceptual integrated system consisting of steam gasification of lignocellulosic biomass, planar-type solid oxide fuel cell, and planar-type solid oxide electrolyzer cell was introduced by Abuadala et al. [76] (entry 3 in Table 2). In particular, the lignocellulosic biomass gasification was performed with a steam/lignocellulosic biomass molar ratio of 0.8 and a temperature of 750–1150 °C under atmospheric pressure. The integrated system could produce H_2 (from the steam decomposed in the solid oxide electrolyzer cell) at a production capacity of 21.8 and 25.2 kg h^{-1}, power, and heat. In addition, the solid oxide fuel and electrolyzer cells each operated at a temperature and pressure of 727 °C and 1.2 bar, respectively, with an internal H_2 consumption by the fuel cell of 8.1–8.6 kg h^{-1}. Consequently, the efficiency of the solid oxide fuel cell was 50.3 %. It was also estimated the unit exergy cost of H_2 ranging from 0.21 to 0.26 USD kWh^{-1} resulted in an electricity cost of 0.105 USD kWh^{-1}.

More recently, an integrated system involving co-gasification of wood and cow manure, solid oxide fuel cell, and micro gas-turbine was proposed by Jia et al. [77] (entry 4 in Table 2 and Fig. 3). In particular, these authors explored the respective impacts of the mass flow rate of the gasifying agent (air) supplied to the gasifier, mass fraction of wood in the wood and cow manure feedstock, and moisture content of the feedstock on the performance of the integrated system. Notably, a decrease in the mass fraction of cow manure in the feedstock and an increase in the mass flow rate of air supplied to the gasifier enhanced the feedstock conversion efficiency of the co-gasification process. In particular, this feedstock conversion and the electrical efficiencies of the integrated system were estimated to be ~45 % at the mass fraction of cow manure of <0.4, moisture content of <0.4, mass flow rate of air of >47 kg h^{-1}, and mass flow rate of the feedstock of 28 kg h^{-1}. Also, as the mass fraction of cow manure in the feedstock increased, the integrated system became less economically feasible. On the other hand, the integrated system became more economically competitive as the initial investment and operation and maintenance costs of the solid oxide fuel cell decreased. Finally, the payback time of the integrated system was estimated to be less than 8 years when the initial investment cost of the solid oxide fuel cell was 7000 € kW^{-1}.

3.3. Integrated with anaerobic digestion

Anaerobic digestion is a biochemical process in which biomass is biologically broken down by microorganisms in the absence of oxygen. In particular, naturally occurring microorganisms digest biomass in anaerobic digestion, resulting in the formation of biogas (a mixture mainly of CH_4 and CO_2) and a solid/liquid residue. The biogas can be used to power internal combustion engines to eventually generate electricity. Anaerobic digestion has been used in different areas/fields for many years, and it is now mature [78].

Wang group [79, 80] developed integrated bioenergy conversion systems involving anaerobic digestion and gasification of lignocellulosic biomass. First, lignocellulosic biomass residue was anaerobically digested in each of these integrated systems to produce biogas that can be used as fuel (entries 5 and 6 in Table 2). The residue from the anaerobic digestion was then gasified to produce syngas that can also be used as fuel. In effect, the integrated system had a ~6 % higher energy efficiency than that of a single system (anaerobic digestion only or gasification only) used for the same biomass conversion [79]. Likewise, an integrated gasification/anaerobic digestion system (Fig. 4) for yard biomass residue conversion first performed anaerobic digestion of the yard biomass residue in the presence of anaerobic sludge [80]. The residue from the anaerobic digestion was then co-gasified with wood chips to produce syngas. As a result of demonstrating the process by varying the operation parameters of the system, the optimum energy efficiency of the system was found to be ~71 % for a residue/wood chips mass ratio of 0.2 and residue moisture content of 30 wt%.

3.4. Integrated with fusion power

Fusion power refers to as the electricity generated by using the heat generated from nuclear fusion reactions [81]. In particular, a nuclear fusion combines two lighter atomic nuclei to form a heavier nucleus, releasing energy. Hence, devices designed to harness this energy are known as nuclear fusion reactors. An interesting integrated renewable energy system that used a nuclear fusion reactor to supply heat to a biomass gasifier was developed by Nam et al. [82, 83]. In particular, a prototype of the nuclear fusion/gasification integrated system (entry 7 in Table 2) had a weight loss of the biomass in the gasification of approximately 73 %, with average endothermic heating of 530 J g^{-1} and a gasification temperature of 600 °C [82]. In addition, the resultant syngas from the integrated system was assumed to be transformed into hydrocarbons through the Fischer-Tropsch process or H_2 through the water-gas shift reaction. Finally, the levelized cost of the hydrocarbon and H_2 as fuels was estimated to be 9.2 USD GJ^{-1} and 8.7 USD GJ^{-1}, respectively. However, an increase in the gasification temperature to 1000 °C was not possible in this integrated system due to technical limitations.

A more recent study conducted by the Nam group [83] further integrated the nuclear fusion/biomass gasification system with a solid oxide fuel cell and gas turbine to enhance the electricity generation. Fig. 5 shows a schematic diagram of this integrated system (entry 8 in Table 2). In particular, at a gasification temperature of 900 °C, the integrated system could produce electricity of 454 MW with a 80 % capacity factor and ~7,000 h time-on-stream in one year. In this, the solid oxide fuel cell produced net electricity of 289 MW, and the overall integrated system efficiency was 30 %. This low efficiency was attributed to the high self-consumption of the nuclear fusion reactor. In effect, the levelized cost of electricity generated by the integrated system was estimated to be 208 USD MWh^{-1}, with an energy return on investment of 3.9.

3.5. Integrated with energy storage systems

Energy storage in a useful form is a major component of our energy use and is often necessary because it is sometimes inconvenient or impossible to convert energy for use when or where it is needed [84]. Few recent studies have integrated the gasification of biomass with energy storage systems. For example, Diyoke and Wu [85] conducted a thermodynamic analysis of a power system composed of biomass gasification and adiabatic compressed-air energy storage to simultaneously produce warm water and generate electricity for domestic use (entry 9 in Table 2). The power system achieved a 1.3-MW peak load power demand through a 1-MW adiabatic compressed-air energy storage system and a 0.3-MW engine fueled with diesel and the syngas produced by the gasification process. In particular, this syngas was produced through the gasification of wood. In effect, the energy, exergy, electrical, and effective electrical efficiencies of the power system were assessed to be about 38 %, 29 %, 30 %, and 34 %, respectively. Although the system could be attractive, particularly for rural areas in developing countries, it could not satisfy the EU criteria for high-efficient co-generation systems because its primary energy saving ratio was not more than 10.

Lin et al. [86] designed a co-generation plant for simultaneous generation of electricity and liquid H_2 involving a lignocellulosic biomass gasification-integrated gas turbine (Rankine cycle) and H_2 liquefaction cycle with an electrolyzer process (entry 10 in Table 2). The liquid H_2 was then stored in a tank for later use. It was found that the mass flow rate of biomass was the most critical parameter for the integrated system of the plant. In effect, the maximum power and H_2 yield that could be achieved with the integrated system were approximately 3400 kW and 14.8 kg h^{-1}, respectively, at a mass flow rate of biomass of 1.9 kg s^{-1}. Also, the minimum total cost rate of the integrated system was estimated to be about 86.6 USD h^{-1} with a greenhouse gas emission of 1.1 kg CO_2 kWh^{-1}.

4. Pyrolysis-based integrated systems

This section introduces and discusses bioenergy-based renewable energy systems that integrate lignocellulosic biomass pyrolysis and other renewable energy technologies (e.g., solar thermal energy and anaerobic digestion). Table 3 summarizes recent representative studies on lignocellulosic biomass pyrolysis-based integrated renewable energy systems.

4.1. Integrated with solar thermal energy

There are few studies in the literature on systems integrating pyrolysis of lignocellulosic biomass with solar thermal energy. For instance, Cheng et al. [87] proposed an integrated renewable energy system of lignocellulosic biomass pyrolysis and solar thermal energy (entry 1 in Table 3). In particular, Cheng et al. performed an energy analysis to evaluate the integrated system, quantitatively expressing the value of the products of the system in terms of equivalent solar thermal energy. So, the total annual energy input of the integrated system was 6,900 trillion solar equivalent Joules (seJ). In addition, the unit energy value, energy yield ratio, environmental load rate, and energy sustainability index of the integrated system were estimated to be approximately 75,000 seJ J^{-1}, 1, 0.6, and 1.7, respectively. Finally, the annual pollutant degradation energy of the integrated system was calculated to be 280 trillion seJ. Hence, it was concluded that the integrated system was not preferable for use with the local renewable resources despite its low environmental impact. Fig. 6 shows this integrated system.

Relatedly, Perkins [88] compared two integrated renewable energy systems, namely solar PV/bio-oil combustion and solar PV/battery storage. The bio-oil used in the combustion was produced from lignocellulosic biomass through pyrolysis. With comparable assumptions on the two integrated systems, the levelized cost of electricity for the solar PV/bio-oil combustion and solar PV/battery storage systems was estimated to be 116 AUD MWh^{-1} and 170 AUD MWh^{-1}, respectively, for a scale of daily electricity production of 240 MWh. These costs indicated that the lignocellulosic biomass pyrolysis-based integrated system could be more competitive than other renewable energy technologies.

4.2. Integrated with anaerobic digestion

Like the lignocellulosic biomass gasification-based integrated renewable energy systems discussed in Sec. 2.3, pyrolysis of the biomass can be integrated with anaerobic digestion of the biomass to achieve high energy recovery from the biomass [89, 90]. In particular, lignocellulosic biomass is first anaerobically digested (often with organic waste) in these systems. The biogas produced from the digestion can then be used as fuel to generate heat or electricity, and the biomass-derived digestate is further pyrolyzed to produce pyrolytic gas, bio-oil, and char. This procedure is schematically described in Fig. 7. The pyrolysis integrated with anaerobic digestion of lignocellulosic biomass can greatly contribute to reducing greenhouse gas emissions and impacts eutrophication and soil acidification more than non-renewable source-based processes do [91].

Monlau et al. [89] investigated the feasibility of an anaerobic digestion/pyrolysis integrated system for lignocellulosic biomass conversion (entry 3 in Table 3). Notably, the solid anaerobic digestate of the integrated system derived from lignocellulosic biomass and animal manure was pyrolyzed at a temperature of 500 °C, producing pyrolytic gas, bio-oil, and char of 8.8, 58.4, and 32.8 wt%, respectively. The LHV of the pyrolytic gas was 15.7 MJ Nm^{-3}, and the higher heating value (HHV) of the bio-oil was 23.5 MJ kg^{-1} after water removal. In addition, the daily electricity generation through the integrated system was approximately 14,100 kWh, 42 % higher than that through the anaerobic digestion (without pyrolysis) of the biomass. Likewise, co-digestion of lignocellulosic biomass (e.g., quinoa residue) and sewage sludge integrated with the pyrolysis of the digestate had a global warming potential of −604 kg CO_2-eq $t_{substrate}^{-1}$, contributed to an ozone depletion of −2.11 mg CFC-11 equivalent $t_{substrate}^{-1}$, and required the use of fossil resources of −6900 MJ $t_{substrate}^{-1}$ [92].

It has been proved that the use of lignocellulosic biomass-derived char enhances the performance of the anaerobic digestion process [93, 94]. In the most recent study, conducted by Deng et al. [90], a bioenergy system with the pyrolysis of lignocellulosic biomass primarily producing wood-derived char that was used to enhance the production of CH_4 during anaerobic digestion of algal biomass, such as seaweed, was proposed as an integrated system (entry 4 in Table 3). This study also demonstrated that the use of the char in the anaerobic digestion of seaweed enhanced the CH_4 yield and the peak CH_4 production rate by 16–17 % and 29–30 %, compared to those of the anaerobic digestion without char, respectively. Further, the integrated system could self-sustain by combusting the pyrolytic gas and surplus char (in excess of the char used in the anaerobic digestion).

4.3. Integrated with a few other renewable energy technologies

A thermochemical biomass conversion-based integrated renewable energy system that involves electricity generation and biochar production from lignocellulosic biomass using different thermochemical processes and renewable energy technologies was proposed by Li et al. [95] as a strategy for achieving negative greenhouse gas emissions. The proposed layout of the integrated system for simultaneous electricity generation/biochar production is given in Fig. 8 (entry 5 in Table 3). Notably, the pyrolysis and gasification of lignocellulosic biomass in the integrated system largely contributed to reducing greenhouse gas emissions by converting the biomass into biochar that was potentially subjected to sol amendment and carbon sequestration. In addition, biomass combustion, photovoltaics, and wind energy were used to generate electricity in the integrated system. Likewise, the syngas and pyrolytic gas of the integrated system were expanded in a gas turbine for electricity generation. Additionally, energy storage was used to control and regulate the electricity generated from different resources according to a varying energy demand. Finally, Li et al. implemented the proposed integrated system on Carabao Island in San Jose, Philippines. This island had an area of 22.1 km^2 and a population of 10,900 people, and the implemented integrated system had a carbon sequestration potential of about 2800 kg CO_2-eq and achieved an estimated daily profit of ~460 USD.

5. Hydrothermal conversion-based integrated systems

This section introduces and discusses bioenergy systems that integrate hydrothermal conversion of lignocellulosic biomass and other renewable energy technologies (e.g., solid oxide fuel cell and anaerobic digestion). Table 4 summarizes recent representative studies on hydrothermal lignocellulosic biomass conversion-based integrated renewable energy systems.

5.1. Integrated with solid oxide fuel cell

Hydrothermal lignocellulosic biomass gasification integrated with solid oxide fuel cell has been designed, modeled, and analyzed by several researchers [96-99]. For example, Toonssen et al. [96] analyzed the thermodynamic performance of three different hydrothermal lignocellulosic biomass gasification, including non-catalytic and catalytic hydrothermal gasification of lignocellulosic biomass, and the one such gasification integrated with a solid oxide fuel cell-gas turbine cycle forming an integrated system. In particular, exergy efficiency of approximately 52 % was achieved for the integrated system with a biomass feedstock containing 80 wt% moisture. Likewise, Facchinetti et al. [99] performed a systematic process integration and optimization of a solid oxide fuel cell-gas turbine cycle fueled with hydrothermally gasified lignocellulosic biomass. This integrated system showed potential for generating electricity from wet biomass with a First Law efficiency of up to 63 %. In addition, biogenic CO_2 generated by the integrated system could be separated simultaneously, which might lead to a negative net CO_2 emission when the biogenic CO_2 was properly treated, used, or sequestrated.

5.2. Integrated with anaerobic digestion

Digestate from anaerobic digestion of lignocellulosic biomass (e.g., wheat straw) conducted at a temperature of 50–60 °C was used as feedstock for hydrothermal carbonization by Reza et al. [100]. The energy recovery efficiency of this integrated system was 60 % and 20 % higher than those of anaerobic digestion and hydrothermal carbonization of the biomass, respectively.

Codignole Luz et al. [101] demonstrated an integrated system using spent coffee ground-derived char produced through hydrothermal carbonization of the spent coffee ground as a substrate in anaerobic digestion of cattle manure (Fig. 9a). In particular, co-anaerobic digestion of cattle manure and the spent coffee ground char at a temperature of 180 °C led to a short lag phase of 11 d, a high CH_4 production rate of 46 mL $g_{\text{volatile solid}}^{-1}$ d^{-1}, and a high CH_4 potential of 491.4 mL $g_{\text{volatile solid}}^{-1}$. Furthermore, this integrated system also had a CH_4 conversion efficiency of up to 32 %. In addition, the temperature at which the char was produced affected the anaerobic digestion performance. Notably, the char produced at a temperature of 180 °C resulted in better CH_4 production performance of the integrated system than the performance resulting from using the char produced at a temperature of 200 °C and 250 °C, respectively, in the system.

More recently, Heidari et al. [102] reported their design of a power generation system integrating hydrothermal carbonization and anaerobic digestion of biomass. In particular, lignocellulosic biomass (e.g., sawdust) was first hydrothermally carbonized in the integrated system to produce char and residual liquid. The char was then used as solid fuel to generate power through the Rankine cycle, and the residual liquid was anaerobically digested to biogas that was used as gaseous fuel to generate power through the Brayton cycle. This system is schematically depicted in Fig. 9b. Heidari et al. also compared the integrated system with direct biomass combustion. The comparison showed that at a lignocellulosic biomass (10 wt% moisture content) feeding rate of 16 g s^{-1}, the integrated system and direct combustion generated power of 95.8 kW and 101 kW, respectively. In addition, given the complexity and high potential capital cost of the integrated system, the direct combustion seemed to be better and simpler than the integrated system for bioenergy conversion from sawdust. Nevertheless, as the moisture content of the biomass increased, the integrated system could be more feasible than the direct combustion.

6. Challenges and future recommendation

Bioenergy conversion from lignocellulosic biomass through a thermochemical process integrated with other renewable energy technologies forming an integrated system has been investigated by different research groups. According to the literature survey, solar thermal energy, solid oxide fuel cells, and anaerobic digestion are renewable energy technologies most commonly integrated with thermochemical conversion processes. Table 5 summarizes advantages and disadvantages of the three renewable energy technologies. Power generation using the integrated systems have been identified as a cost-effective, sustainable, and feasible solution contributing to climate change mitigation. However, further development of the integrated system requires the devising of various strategies to overcome the challenges that remain and achieve the associated research objectives, as follows:

- Although various designs have been proposed for the integrated system, they are mostly conceptual (i.e., model- and simulation-based), and only very few studies on the system are experimental. In other words, experimental validation of the proposed model/simulated configurations of the system by the studies under real outdoor conditions is required. In essence, more experiment-based designs of the integrated system need to be developed to increase the feasibility of the system.

- The overall biomass conversion efficiency of the integrated system is greatly affected by the characteristics of the lignocellulosic biomass feedstock (e.g., moisture content and composition of the biomass) of the system. However, the feedstock characteristics are highly associated with the origin, storage conditions (e.g., humidity and temperature), period of storage, etc., of the biomass [103]. Therefore, the integrated system can hardly give instant responses to a varying energy demanded from the system. Relatedly, the collection and transportation of lignocellulosic biomass are also a concern under the integrated system. In this regard, devising an effective dispatch strategy for the biomass and addressing the power fluctuation problems in the grid-connected integrated system are essential parts of future research on the system.
- Lignocellulosic biomass with a high content of moisture and ash (higher than 10 wt% each) can cause tar formation and slugging inside the thermochemical process reactor, such as a gasifier [104]. Even though this issue of tar formation and slugging are critically associated with continuous feeding, studies into pre-treatment of lignocellulosic biomass to remove the biomass moisture and ash contents have rarely been carried out. Hence, the research focus is required to overcome the issue and gain more attention for installing the integrated system.
- A continuous and steady supply of lignocellulosic biomass to the integrated system is important. Therefore, as stated before, the strategy for the collection and transportation of lignocellulosic biomass must be well established and adopted depending on the local environments and situations of the integrated system to make the system more viable. Further, a complete technoeconomic analysis of the integrated system considering the supply of lignocellulosic biomass needs to be conducted to estimate the potential costs for the scale-up of the system.

- More research is also required in the form of a comparative analysis of various thermochemical process/renewable energy resources of the integrated system considering the specific location of the system and energy demanded from the system.
- The feasibility of the integrated system is highly dependent on the location of the system because the types of renewable resources and associated conditions largely depend on this location. Thus, the location of interest for the integrated system must be carefully considered to optimize various configurations of the integrated system based on the cost of power generation per system unit.
- Although lignocellulosic biomass-based power generation is beneficial compared to fossil fuel-based power generation in terms of renewability and sustainability, a lack of social awareness hinders the development of the integrated system. Hence, governments need to persuade people to install plants based on the integrated system for power generation. Meanwhile, the encouragement by non-governmental and social organizations to use bioenergy technologies has been playing an important role in promoting the use of the integrated system [105]. Also, societal and industrial needs and government legislation can further enhance the viability of the integrated system.
- Despite the abundance of lignocellulosic biomass worldwide [106], the biomass may still not be enough to meet the energy demand in certain regions. Notably, the global generation of municipal solid waste has been increasing massively, approaching 3.4 billion metric tons of municipal solid waste by 2050 [107]. Municipal solid waste is a conceivable feedstock that can be converted using thermochemical processes to generate power and/or heat [108, 109]. In addition, the use of lignocellulosic biomass blended with municipal solid waste as feedstock for the conversion of the feedstock using a thermochemical process, when integrated with other renewable energy technologies (e.g., co-gasification and co-pyrolysis) with flexible blending ratios of the feedstock, can be an

effective strategy to satisfy a varying local (even central) energy demand [110, 111].

7. Conclusions

This study performed an extensive review of thermochemical lignocellulosic biomass processing (e.g., gasification, pyrolysis, and hydrothermal processing of the biomass) integrated with other renewable energy technologies (such as solar thermal energy, solid oxide fuel cell, anaerobic digestion, fusion power, and energy storage system). In particular, current technical achievements in thermochemical conversion of lignocellulosic biomass-based integrated renewable energy systems for the generation of biopower were summarized and discussed with the respective economic and environmental aspects of the systems in this review. Even though the integrated systems have shown promise for biopower generation, some research questions could be raised by critical analysis of the existing literature. Hence, recommendations for future research and development of the integrated system were also provided, which might help answer the questions. Hence, continuous efforts should be dedicated to improving the viability and effectiveness of the integrated system in the future.

Appendix

Emergy: A way to count sunlight energy required to make a higher- quality energy and transformation ratios [112]

Exergy: the amount of work (i.e., entropy-free energy) a system can perform when it is brought into thermodynamic equilibrium with its environment [113]

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References

[1] Saxena RC, Adhikari DK, Goyal HB. Biomass-based energy fuel through biochemical routes: a review. Renew Sust Energ Rev. 2009;13:167-78.

[2] Chauhan A, Saini RP. Techno-economic feasibility study on integrated renewable energy system for an isolated community of India. Renew Sust Energ Rev. 2016;59:388-405.

[3] Han J, Byun J, Kwon O, Lee J. Climate variability and food waste treatment: analysis for bioenergy sustainability. Renew Sust Energ Rev. 2022;160:112336.

[4] Dahmen N, Lewandowski I, Zibek S, Weidtmann A. Integrated lignocellulosic value chains in a growing bioeconomy: status quo and perspectives. Glob Change Biol Bioenergy. 2019;11:107-17.

[5] Guragain YN, Vadlani PV. Renewable biomass utilization: a way forward to establish sustainable chemical and processing industries. Clean Technol. 2021;3:243-59.

[6] Kim S, Tsang YF, Kwon EE, Lin K-YA, Lee J. Recently developed methods to enhance stability of heterogeneous catalysts for conversion of biomass-derived feedstocks. Korean J Chem Eng. 2019;36:1-11.

[7] Kim S, Kwon EE, Kim YT, Jung S, Kim HJ, Huber GW, et al. Recent advances in hydrodeoxygenation of biomass-derived oxygenates over heterogeneous catalysts. Green Chem. 2019;21:3715-43.

[8] Wang C, Zhang X, Liu Q, Zhang Q, Chen L, Ma L. A review of conversion of lignocellulose biomass to liquid transport fuels by integrated refining strategies. Fuel Process Technol. 2020;208:106485.

[9] Park C, Lee J. Recent achievements in CO_2-assisted and CO_2-catalyzed biomass conversion reactions. Green Chem. 2020;22:2628-42.

[10] Kim J, park H, Han J, Lee J. A strategy for food waste-to-biofuels: co-production of gasoline alternatives from volatile fatty acids. J Clean Prod. 2022;348:131408.

[11] Sun C, Ren H, Sun F, Hu Y, Liu Q, Song G, et al. Glycerol organosolv pretreatment can unlock lignocellulosic biomass for production of fermentable sugars: present situation and challenges. Bioresour Technol. 2022;344:126264.

[12] Nawaz S, Ahmad M, Asif S, Klemeš JJ, Mubashir M, Munir M, et al. Phyllosilicate derived catalysts for efficient conversion of lignocellulosic derived biomass to biodiesel: a review. Bioresour Technol. 2022;343:126068.

[13] Gan J, Iqbal HMN, Show PL, Rahdar A, Bilal M. Upgrading recalcitrant lignocellulosic biomass hydrolysis by immobilized cellulolytic enzyme–based nanobiocatalytic systems: a review. Biomass Conv Bioref. 2022:DOI: 10.1007/s13399-022-02642-7.

[14] Lee J, Choi D, Kwon EE, Ok YS. Functional modification of hydrothermal liquefaction products of microalgal biomass using CO_2. Energy. 2017;137:412-8.

[15] You S, Ok YS, Chen SS, Tsang DCW, Kwon EE, Lee J, et al. A critical review on sustainable biochar system through gasification: energy and environmental applications. Bioresour Technol. 2017;246:242-53.

[16] Lee J, Sarmah AK, Kwon EE. Production and formation of biochar. In: Ok YS, Tsang DCW, Bolan N, Novak JM, editors. Biochar from Biomass and Waste: Elsevier; 2019. p. 3-18.

[17] Xu Y, Yang K, Zhou J, Zhao G. Coal-biomass co-firing power generation technology: current status, challenges and policy implications. Sustainability. 2020;12:3692.

[18] Yin XL, Wu CZ, Zheng SP, Chen Y. Design and operation of a CFB gasification and power generation system for rice husk. Biomass Bioenergy. 2002;23:181-7.

[19] Hiloidhari M, Baruah DC. Rice straw residue biomass potential for decentralized electricity generation: a GIS based study in Lakhimpur district of Assam, India. Energy Sustain Dev. 2011;15:214-22.

[20] Shackley S, Carter S, Knowles T, Middelink E, Haefele S, Haszeldine S. Sustainable gasification–biochar systems? a case-study of rice-husk gasification in Cambodia, Part II: Field trial results, carbon abatement, economic assessment and conclusions. Energy Policy. 2012;41:618-23.

[21] Cutz L, Berndes G, Johnsson F. A techno-economic assessment of biomass co-firing in Czech Republic, France, Germany and Poland. Biofuels, Bioprod Bioref. 2019;13:1289-305.

[22] Carley S. State renewable energy electricity policies: an empirical evaluation of effectiveness. Energy Policy. 2009;37:3071-81.

[23] Prasartkaew B, Kumar S. A low carbon cooling system using renewable energy resources and technologies. Energy Build. 2010;42:1453-62.

[24] Rajoriya A, Fernandez E. Sustainable energy generation using hybrid energy system for remote hilly rural area in India. Int J Sustain Eng. 2010;3:219-27.

[25] Malik P, Awasthi M, Sinha S. Biomass-based gaseous fuel for hybrid renewable energy systems: an overview and future research opportunities. Int J Energy Res. 2021;45:3464-94.

[26] Bernal-Agustín JL, Dufo-López R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sust Energ Rev. 2009;13:2111-8.

[27] Wang X, Palazoglu A, El-Farra NH. Operational optimization and demand response of hybrid renewable energy systems. Appl Energy. 2015;143:324-35.

[28] Ashok S. Optimised model for community-based hybrid energy system. Renew Energy. 2007;32:1155-64.

[29] Pérez-Navarro A, Alfonso D, Álvarez C, Ibáñez F, Sánchez C, Segura I. Hybrid biomass-wind power plant for reliable energy generation. Renew Energy. 2010;35:1436-43.

[30] Singh A, Baredar P. Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system. Energy Rep. 2016;2:254-60.

[31] Kozlov AN, Tomin NV, Sidorov DN, Lora EES, Kurbatsky VG. Optimal operation control of PV-biomass gasifier-diesel-hybrid systems using reinforcement learning techniques. Energies. 2020;13:2632.

[32] Sotoodeh AF, Ahmadi F, Ghaffarpour Z, Ebadollahi M, Nasrollahi H, Amidpour M. Performance analyses of a waste-to-energy multigeneration system incorporated with thermoelectric generators. Sustain Energy Technol Assess. 2022;49:101649.

[33] Safarian S, Unnthorsson R, Richter C. Performance analysis and environmental assessment of small-scale waste biomass gasification integrated CHP in Iceland. Energy. 2020;197:117268.

[34] Park C, Lee N, Kim J, Lee J. Co-pyrolysis of food waste and wood bark to produce hydrogen with minimizing pollutant emissions. Environ Pollut. 2021;270:116045.

[35] Kim S, Lee N, Lee SW, Kim YT, Lee J. Upcycling of waste teabags via catalytic pyrolysis in carbon dioxide over HZSM-11. Chem Eng J. 2021;412:128626.

[36] Lee Y, Lee SW, Tsang YF, Kim YT, Lee J. Engineered rice-straw biochar catalysts for the production of value-added chemicals from furan. Chem Eng J. 2020;387:124194.

[37] Lee N, Joo J, Lin K-YA, Lee J. Thermochemical conversion of mulching film waste via pyrolysis with the addition of cattle excreta. J Environ Chem Eng. 2021;9:106362.

[38] Kim S, Byun J, Park H, Lee N, Han J, Lee J. Energy-efficient thermal waste treatment process with no CO_2 emission: a case study of waste tea bag. Energy. 2022;241:122876.

[39] Banks SW, Bridgwater AV. Chapter 14 - Catalytic fast pyrolysis for improved liquid quality. In: Luque R, Lin CSK, Wilson K, Clark J, editors. Handbook of Biofuels Production (Second Edition): Woodhead Publishing; 2016. p. 391-429.

[40] Lee J, Kim K-H, Kwon EE. Biochar as a catalyst. Renew Sust Energ Rev. 2017;77:70-9.

[41] Kwon EE, Kim S, Lee J. Pyrolysis of waste feedstocks in CO_2 for effective energy recovery and waste treatment. J CO_2 Util. 2019;31:173-80.

[42] Grande L, Pedroarena I, Korili SA, Gil A. Hydrothermal liquefaction of biomass as one of the most promising alternatives for the synthesis of advanced liquid biofuels: a review. Materials. 2021;14:5286.

[43] Matsumura Y. Chapter 9 - Hydrothermal gasification of biomass. In: Pandey A, Bhaskar T, Stöcker M, Sukumaran RK, editors. Recent Advances in Thermo-Chemical Conversion of Biomass. Boston: Elsevier; 2015. p. 251-67.

[44] Yoganandham ST, Sathyamoorthy G, Renuka RR. Chapter 8 - Emerging extraction techniques: hydrothermal processing. In: Torres MD, Kraan S, Dominguez H, editors. Sustainable Seaweed Technologies: Elsevier; 2020. p. 191-205.

[45] Kambo HS, Dutta A. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew Sust Energ Rev. 2015;45:359-78.

[46] Yan X, Ma J, Wang W, Zhao Y, Zhou J. The effect of different catalysts and process parameters on the chemical content of bio-oils from hydrothermal liquefaction of sugarcane bagasse. BioRes. 2018;13:997-1018.

[47] Ahmed Baloch H, Nizamuddin S, Siddiqui MTH, Mubarak NM, Dumbre DK, Srinivasan MP, et al. Sub-supercritical liquefaction of sugarcane bagasse for production of bio-oil and char: effect of two solvents. J Environ Chem Eng. 2018;6:6589-601.

[48] Ariyawansha T, Abeyrathna D, Ahamed T, Noguchi R. Integrated bagasse utilization system based on hydrothermal liquefaction in sugarcane mills: theoretical approach compared with present practices. Biomass Conv Bioref. 2022;12:27-37.

[49] Dunlap RA. Chapter 9 - Electricity from solar energy. Sustainable Energy (2nd edition). Boston, MA, USA: Cengage; 2019.

[50] Law EW, Kay M, Taylor RA. Calculating the financial value of a concentrated solar thermal plant operated using direct normal irradiance forecasts. Sol Energy. 2016;125:267-81.

[51] Martino A. Sunshine to petrol: solar recycling of carbon dioxide into hydrocarbon fuels. Albuquerque, NM, USA: Sandia National Laboratories; 2013.

[52] Hertwich EG, Zhang X. Concentrating-solar biomass gasification process for a 3rd generation biofuel. Environmental Science & Technology. 2009;43:4207-12.

[53] Melchior T, Perkins C, Lichty P, Weimer AW, Steinfeld A. Solar-driven biochar gasification in a particle-flow reactor. Chem Eng Process: Process Intensif. 2009;48:1279-87.

[54] Chen J, Lu Y, Guo L, Zhang X, Xiao P. Hydrogen production by biomass gasification in supercritical water using concentrated solar energy: system development and proof of concept. Int J Hydrog Energy. 2010;35:7134-41.

[55] Lichty P, Perkins C, Woodruff B, Bingham C, Weimer A. Rapid high temperature solar thermal biomass gasification in a prototype cavity reactor. J Sol Energy Eng. 2010;132.

[56] Gordillo ED, Belghit A. A downdraft high temperature steam-only solar gasifier of biomass char: a modelling study. Biomass Bioenergy. 2011;35:2034-43.

[57] Piatkowski N, Wieckert C, Weimer AW, Steinfeld A. Solar-driven gasification of carbonaceous feedstock—a review. Energy Environ Sci. 2011;4:73-82.

[58] Ravaghi-Ardebili Z, Manenti F, Corbetta M, Pirola C, Ranzi E. Biomass gasification using low-temperature solar-driven steam supply. Renew Energy. 2015;74:671-80.

[59] Tanaka Y, Mesfun S, Umeki K, Toffolo A, Tamaura Y, Yoshikawa K. Thermodynamic performance of a hybrid power generation system using biomass gasification and concentrated solar thermal processes. Appl Energy. 2015;160:664-72.

[60] Kaniyal AA, van Eyk PJ, Nathan GJ. Dynamic modeling of the coproduction of liquid fuels and electricity from a hybrid solar gasifier with various fuel blends. Energy Fuels. 2013;27:3556-69.

[61] Muroyama A, Shinn T, Fales R, Loutzenhiser PG. Modeling of a dynamically-controlled hybrid solar/autothermal steam gasification reactor. Energy Fuels. 2014;28:6520-30.

[62] Li X, Shen Y, Kan X, Hardiman TK, Dai Y, Wang C-H. Thermodynamic assessment of a solar/autothermal hybrid gasification CCHP system with an indirectly radiative reactor. Energy. 2018;142:201-14.

[63] Godula-Jopek DIhA, Westenberger AF. Fuel cell types: PEMFC/DMFC/AFC/PAFC//MCFC/SOFC. In: Cabeza LF, editor. Encyclopedia of Energy Storage. Oxford: Elsevier; 2022. p. 250-65.

[64] Badwal SPS, Giddey S, Munnings C, Kulkarni A. Review of progress in high temperature solid oxide fuel cells. J Aust Ceram Soc. 2014;50:23-37.

[65] Ud Din Z, Zainal ZA. Biomass integrated gasification–SOFC systems: technology overview. Renew Sust Energ Rev. 2016;53:1356-76.

[66] Athanasiou C, Coutelieris F, Vakouftsi E, Skoulou V, Antonakou E, Marnellos G, et al. From biomass to electricity through integrated gasification/SOFC system-optimization and energy balance. Int J Hydrog Energy. 2007;32:337-42.

[67] Cordiner S, Feola M, Mulone V, Romanelli F. Analysis of a SOFC energy generation system fuelled with biomass reformate. Appl Therm Eng. 2007;27:738-47.

[68] Colpan CO, Hamdullahpur F, Dincer I, Yoo Y. Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems. Int J Hydrog Energy. 2010;35:5001-9.

[69] Jia J, Abudula A, Wei L, Sun B, Shi Y. Thermodynamic modeling of an integrated biomass gasification and solid oxide fuel cell system. Renew Energy. 2015;81:400-10.

[70] Sucipta M, Kimijima S, Suzuki K. Performance analysis of the SOFC–MGT hybrid system with gasified biomass fuel. J Power Sources. 2007;174:124-35.

[71] Fryda L, Panopoulos KD, Kakaras E. Integrated CHP with autothermal biomass gasification and SOFC–MGT. Energy Convers Manag. 2008;49:281-90.

[72] Bang-Møller C, Rokni M, Elmegaard B. Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. Energy. 2011;36:4740-52.

[73] Toonssen R, Sollai S, Aravind PV, Woudstra N, Verkooijen AHM. Alternative system designs of biomass gasification SOFC/GT hybrid systems. Int J Hydrog Energy. 2011;36:10414-25.

[74] Campitelli G, Cordiner S, Gautam M, Mariani A, Mulone V. Biomass fueling of a SOFC by integrated gasifier: Study of the effect of operating conditions on system performance. Int J Hydrog Energy. 2013;38:320-7.

[75] Borji M, Atashkari K, Ghorbani S, Nariman-Zadeh N. Parametric analysis and Pareto optimization of an integrated autothermal biomass gasification, solid oxide fuel cell and micro

gas turbine CHP system. Int J Hydrog Energy. 2015;40:14202-23.

[76] Abuadala A, Dincer I. Exergoeconomic analysis of a hybrid system based on steam biomass gasification products for hydrogen production. Int J Hydrog Energy. 2011;36:12780-93.

[77] Jia J, Shu L, Zang G, Xu L, Abudula A, Ge K. Energy analysis and techno-economic assessment of a co-gasification of woody biomass and animal manure, solid oxide fuel cells and micro gas turbine hybrid system. Energy. 2018;149:750-61.

[78] Jenkins N, Ekanayake J. Chapter 8 - Bioenergy. Renewable Energy Engineering. United Kingdom: Cambridge University Press; 2017.

[79] Kan X, Yao Z, Zhang J, Tong YW, Yang W, Dai Y, et al. Energy performance of an integrated bio-and-thermal hybrid system for lignocellulosic biomass waste treatment. Bioresour Technol. 2017;228:77-88.

[80] Yao Z, Li W, Kan X, Dai Y, Tong YW, Wang C-H. Anaerobic digestion and gasification hybrid system for potential energy recovery from yard waste and woody biomass. Energy. 2017;124:133-45.

[81] Dunlap RA. Chapter 7 - Energy from nuclear fusion. Sustainable Energy (2nd edition). Boston, MA, USA: Cengage; 2019.

[82] Nam H, Mukai K, Konishi S, Nam K. Biomass gasification with high temperature heat and economic assessment of fusion-biomass hybrid system. Fusion Eng Des. 2019;146:1838-42.

[83] Nam H, Ibano K, Konishi S. Cost analysis and energy return on investment of fuel cell and gas turbine integrated fusion-biomass hybrid system; application of a small scale conceptual fusion reactor GNOME. Energy. 2020;203:117825.

[84] Dunlap RA. Chapter 18 - Energy storage. Sustainable Energy (2nd edition). Boston, MA, USA: Cengage; 2019.

[85] Diyoke C, Wu C. Thermodynamic analysis of hybrid adiabatic compressed air energy storage system and biomass gasification storage (A-CAES + BMGS) power system. Fuel. 2020;271:117572.

[86] Lin H, Wu X, Ayed H, Mouldi A, Abbas SZ, Ebrahimi-Moghadam A. A new biomass gasification driven hybrid system for power and liquid hydrogen cogeneration: parametric study and multi-objective evolutionary optimization. Int J Hydrog Energy. 2022:in press, DOI: 10.1016/j.ijhydene.2022.01.110.

[87] Cheng J, Zhang C, Sun J, Qiu L. Assessing the sustainable abilities of a pilot hybrid solar-pyrolysis energy system using emergy synthesis. Int J Energy Res. 2020;44:2909-24.

[88] Perkins G. Techno-economic comparison of the levelised cost of electricity generation from solar PV and battery storage with solar PV and combustion of bio-crude using fast pyrolysis of biomass. Energy Convers Manag. 2018;171:1573-88.

[89] Monlau F, Sambusiti C, Antoniou N, Barakat A, Zabaniotou A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. Appl Energy. 2015;148:32-8.

[90] Deng C, Lin R, Kang X, Wu B, O'Shea R, Murphy JD. Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis. Renew Sust Energ Rev. 2020;128:109895.

[91] Righi S, Bandini V, Marazza D, Baioli F, Torri C, Contin A. Life cycle assessment of high ligno-cellulosic biomass pyrolysis coupled with anaerobic digestion. Bioresour Technol. 2016;212:245-53.

[92] Caiardi F, Belaud J-P, Vialle C, Monlau F, Tayibi S, Barakat A, et al. Waste-to-energy innovative system: assessment of integrating anaerobic digestion and pyrolysis technologies. Sustain Prod Consum. 2022;31:657-69.

[93] Salman CA, Schwede S, Thorin E, Yan J. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. Appl Energy. 2017;204:1074-83.

[94] Sawatdeenarunat C, Nam H, Adhikari S, Sung S, Khanal SK. Decentralized biorefinery for lignocellulosic biomass: integrating anaerobic digestion with thermochemical conversion. Bioresour Technol. 2018;250:140-7.

[95] Li L, Yao Z, You S, Wang C-H, Chong C, Wang X. Optimal design of negative emission hybrid renewable energy systems with biochar production. Appl Energy. 2019;243:233-49.

[96] Toonssen R, Aravind PV, Smit G, Woudstra N, Verkooijen AHM. System study on hydrothermal gasification combined with a hybrid solid oxide fuel cell gas turbine. Fuel Cells. 2010;10:643-53.

[97] Gassner M, Vogel F, Heyen G, Maréchal F. Optimal process design for the polygeneration of SNG, power and heat by hydrothermal gasification of waste biomass: process optimisation for selected substrates. Energy Environ Sci. 2011;4:1742-58.

[98] Gassner M, Vogel F, Heyen G, Maréchal F. Optimal process design for the polygeneration of SNG, power and heat by hydrothermal gasification of waste biomass: thermo-economic process modelling and integration. Energy Environ Sci. 2011;4:1726-41.

[99] Facchinetti E, Gassner M, D'Amelio M, Marechal F, Favrat D. Process integration and optimization of a solid oxide fuel cell – Gas turbine hybrid cycle fueled with hydrothermally gasified waste biomass. Energy. 2012;41:408-19.

[100] Reza MT, Werner M, Pohl M, Mumme J. Evaluation of integrated anaerobic digestion and hydrothermal carbonization for bioenergy production. J Vis Exp. 2014;88:e51734.

[101] Codignole Luz F, Volpe M, Fiori L, Manni A, Cordiner S, Mulone V, et al. Spent coffee enhanced biomethane potential via an integrated hydrothermal carbonization-anaerobic digestion process. Bioresour Technol. 2018;256:102-9.

[102] Heidari M, Salaudeen S, Norouzi O, Acharya B, Dutta A. Numerical comparison of a combined hydrothermal carbonization and anaerobic digestion system with direct combustion

of biomass for power production. Processes. 2020;8:43.

[103] Cutz L, Tiringer U, Gilvari H, Schott D, Mol A, de Jong W. Microstructural degradation during the storage of biomass pellets. Commun Mater. 2021;2:2.

[104] Asadullah M. Barriers of commercial power generation using biomass gasification gas: a review. Renew Sust Energ Rev. 2014;29:201-15.

[105] Buragohain B, Mahanta P, Moholkar VS. Biomass gasification for decentralized power generation: the Indian perspective. Renew Sust Energ Rev. 2010;14:73-92.

[106] Haberzettl J, Hilgert P, von Cossel M. A critical review on lignocellulosic biomass yield modeling and the bioenergy potential from marginal land. Agronomy. 2021;11:2397.

[107] Tiseo I. Global waste generation. Statista; 2022.

[108] Tamili N, Chuan LK, Sulaiman SA, Moni MNZ, Inayat M, Lo MYK. Effect of grass and coconut shell blending ratio on the performance of syngas. MATEC Web Conf. 2018;225:02001.

[109] Inayat M, Sulaiman SA. Effect of blending ratio on quality of producer gas from co-gasification of wood and coconut residual. MATEC Web Conf. 2018;225:05005.

[110] Rentizelas AA, Tolis AI, Tatsiopoulos IP. Combined municipal solid waste and biomass system optimization for district energy applications. Waste Manage. 2014;34:36-48.

[111] Hameed Z, Aslam M, Khan Z, Maqsood K, Atabani AE, Ghauri M, et al. Gasification of municipal solid waste blends with biomass for energy production and resources recovery: current status, hybrid technologies and innovative prospects. Renew Sust Energ Rev. 2021;136:110375.

[112] Pincetl S. A living city: using urban metabolism analysis to view cities as life forms. In: Zeman F, editor. Metropolitan Sustainability: Woodhead Publishing; 2012. p. 3-25.

[113] Jørgensen SE, Svirezhev YM. Work, exergy and information. In: Jørgensen SE, Svirezhev YM, editors. Towards a Thermodynamic Theory for Ecological Systems. Oxford: Pergamon; 2004. p. 95-126.

Tables

Table 1. Advantages and disadvantages of thermochemical conversion processes dealt with in this review.

Thermochemical conversion process	Advantage	Disadvantage
Gasification	● Wide applications of the product (e.g., syngas) ● Low pollutant emissions	● Needs for product pretreatment and washing ● Requirement of high temperature
Pyrolysis	● Feedstock flexibility ● Product flexibility (producing a combination of solid, liquid and gaseous products) ● Relatively easily controllable product distribution (by simply changing operating parameters such as temperature and heating rate)	● Complex product composition ● Low gas productivity ● Corrosion of downstream equipment caused by tar
Hydrothermal conversion	● High conversion efficiency ● Relatively easy operation	● Relatively longer reaction time ● Complex proposition of oil product

Table 2. Recent representative bioenergy systems integrating gasification of lignocellulosic biomass with other renewable energy technologies.

Entry	Biomass feedstock	System configuration	Application	System performance	Economic assessment	Ref.
1	Lignocellulosic biomass	Gasification – concentrated solar thermal power	Electricity generation	● Marginal electricity generation of 5 MW ● Highest marginal efficiency of 21 %	Not performed	[59]
2	Redwood	Hybrid autothermal and solar thermal gasifications	Driving combined cooling, heating, and power systems	● Heating, cooling, and power enhanced by 24 %, 1.3 %, and 27.3 %, respectively, under autothermal/solar thermal hybrid mode	Not performed	[62]
3	Sawdust	Gasification – solid oxide fuel cell – solid oxide electrolyzer cell	H_2 production	● Net hydrogen yield of 13.7–16.6 kg h^{-1}, depending on the gasification temperature	● Unit exergy cost of H_2 ranging from 0.06 USD MJ^{-1} to 0.07 USD MWh^{-1} ● Electricity cost of 0.03 USD MJ^{-1}	[76]
4	Wood and cow manure	Co-gasification – solid oxide fuel cell	Electricity generation	● Combined heat and power efficiency of 69 % ● Heat generation of ~0.02 MW at a wood/cow manure ratio of 9	● Net present value of 112,260 € ● Internal rate of return of 18.5 % at a 6-year payback period	[77]
5	Lignocellulosic horticultural biomass	Anaerobic digestion – gasification	Gaseous fuel production	● Highest overall system efficiency of 75.2 % at an organic loading rate of 11.3 g L^{-1} d^{-1}	Not performed	[79]

6	Yard residue and wood chips	Anaerobic digestion – co-gasification	Gaseous fuel production	● Highest energy efficiency of 70.7 % at a residue/wood mass ratio of 0.2 and residue moisture content of 30 wt%	Not performed	[80]
7	Lignocellulosic biomass	Fusion power – gasification	Hydrocarbon fuel or H_2 production	● Average biomass conversion during gasification of 73 % ● Average endothermic heat of 0.53 MJ kg^{-1} at a temperature of 600 °C	● Levelized cost of liquid hydrocarbon fuel of 0.46 USD L^{-1} ● Levelized cost of gaseous H_2 of 1.05 USD kg^{-1}	[82]
8	Lignocellulosic biomass residue	Fusion power – gasification – solid oxide fuel cell	Electricity generation	● Electricity generated from the system was 454 MW with a capacity factor of 80 %, time-on-stream of ~7,000 h in one year, and gasification temperature of 900 °C ● Overall system efficiency of 30 %	● Levelized cost of electricity of 0.058 USD MJ^{-1} ● Energy return on investment of 3.9	[83]
9	Lignocellulosic biomass	Adiabatic compressed air energy storage – gasification	Electricity generation and energy storage	● Overall energy efficiency of ~ 38 % ● Overall exergy efficiency of ~ 29 % ● Electrical efficiency of 30 % ● Effective electrical efficiency of 34 %	Not performed	[85]
10	Lignocellulosic biomass	Gasification – hydrogen liquefaction – electrolyzer	Electricity generation, energy storage, and H_2 production and storage	● Maximum electricity generation of ~3.4 MW ● Maximum hydrogen production rate of 14.8 kg h^{-1} at a biomass mass flow rate of 1.94 kg s^{-1}	● Minimum total cost rate of 86.61 USD h^{-1}	[86]

Table 3. Recent representative bioenergy systems integrating pyrolysis of lignocellulosic biomass with other renewable energy technologies.

Entry	Biomass feedstock	System configuration	Application	System performance	Economic assessment	Environmental impact	Ref.
1	Apple wood	Pyrolysis – solar thermal energy	Heat generation and pyrolytic product production	● Total emergy input of 6.9×10^{15} solar equivalent Joules (seJ) y^{-1} ● Unit emergy value of 7.45×10^{4} seJ J^{-1} ● Renewability of 63.51 % ● Emergy yield ratio of 1 ● Environmental load rate of 0.57 ● Emergy sustainability index of 1.74	Not performed	● Pollutant degradation emergy of 2.77×10^{14} seJ y^{-1}	[87]
2	Lignocellulosic biomass	Bio-oil combustion – photovoltaics	Electricity generation	Not specified	● Cost of 0.032 AUD MJ^{-1} for a scale of daily electricity generation of 864,000 MJ	Not assessed	[88]
3	Lignocellulosic biomass	Anaerobic digestion – pyrolysis	Electricity generation and pyrolytic product production	● 8.8 wt. % pyrolytic gas (LHV of 15.7 MJ Nm^{-3}); 58.4 wt% bio-oil (HHV of 23.5 MJ kg^{-1}), and 32.8 wt% char ● Daily electricity generation of ~50,000 MJ	Not performed	Not assessed	[89]

4	Seaweed/wood	Pyrolysis – anaerobic digestion	CH_4 production	● CH_4 yield of up to 325 mL $g_{\text{volatile solid}}^{-1}$ ● CH_4 production rate of up to 35 mL $g_{\text{volatile solid}}^{-1}$ d^{-1} ● Self-sustained all the heat demand	Not performed	Not assessed	[90]
5	Lignocellulosic biomass	● Biochar production: gasification – pyrolysis ● Electricity generation: biomass combustion – biomass gasification – biomass pyrolysis – photovoltaics – wind power – vanadium redox battery-based energy storage system	Biochar production and electricity generation	● Solar power of 0.162 MW (1038 PV panels) ● Wind power of 0.184 MW (47 wind turbines) ● Biomass combustion of 0.257 MW ● Biomass gasification of 0.049 MW ● Biomass pyrolysis of 0.004 MW ● Energy storage of 0.077 MW (vanadium redox battery)	● Daily net cash flow of 455 USD d^{-1}	● Greenhouse gas emissions of −2795 kg CO_2-eq d^{-1}	[95]

Table 4. Recent representative bioenergy systems integrating hydrothermal conversion of lignocellulosic biomass with other renewable energy technologies.

Entry	Biomass feedstock	System configuration	Application	System performance	Economic assessment	Environmental impact	Ref.
1	Lignocellulosic biomass	Hydrothermal gasification – solid oxide fuel cell	Power generation	● First Law efficiency of up to 63 %	Not performed	Not assessed	[99]
2	Wheat straw	Anaerobic digestion – hydrothermal carbonization	Energy recovery	● Energy content of char of 29.6 MJ kg^{-1} ● Energy recovery of 13.2 MJ kg^{-1}	Not performed	Not assessed	[100]
3	Spent coffee ground	Hydrothermal carbonization – anaerobic digestion	CH_4 production	● Lag phase of 11 d ● CH_4 production rate of 46 mL $g_{volatile\ solid}^{-1}\ d^{-1}$ ● CH_4 potential of 491.4 mL $g_{volatile\ solid}^{-1}$ ● CH_4 conversion efficiency of up to 32 %	Not performed	Not assessed	[101]
4	Sawdust	Hydrothermal carbonization – anaerobic digestion	Power generation	● Power generation of 0.096 MW at a biomass (10 wt% moisture content) feeding rate of 16 g s^{-1}	Not performed	Not assessed	[102]

Table 5. Advantages and disadvantages of renewable energy technologies commonly integrated thermochemical conversion processes.

Thermochemical conversion process integrated with:	Advantage	Disadvantage
Solar thermal energy	● No pollutant emission ● High space efficiency compared to photovoltaics ● Strong industrial-base capability	● Potential intermittent nature ● Dependency on weather
Solid oxide fuel cell	● Fuel flexibility ● Better ability to tolerate impurities ● High efficiency for electricity generation ● Low pollutant emissions	● Need for long start-up time ● Thermal stability required for component materials
Anaerobic digestion	● Abundant available feedstocks ● Operative from small onsite scales to large waste disposal facilities	● Highly sensitive to operating parameters ● Byproduct production

Figures

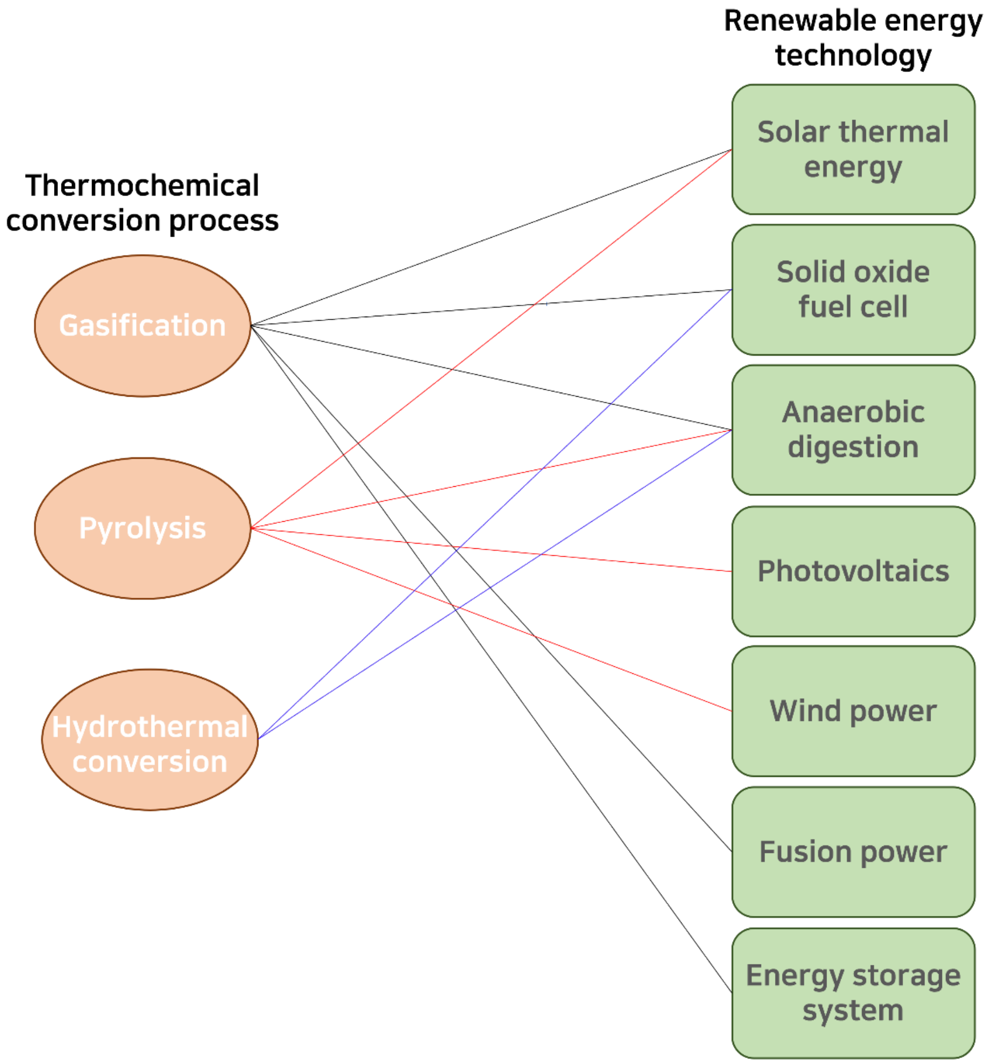

Fig. 1. Configurations of various hybrid renewable energy systems based on thermochemical conversion processes.

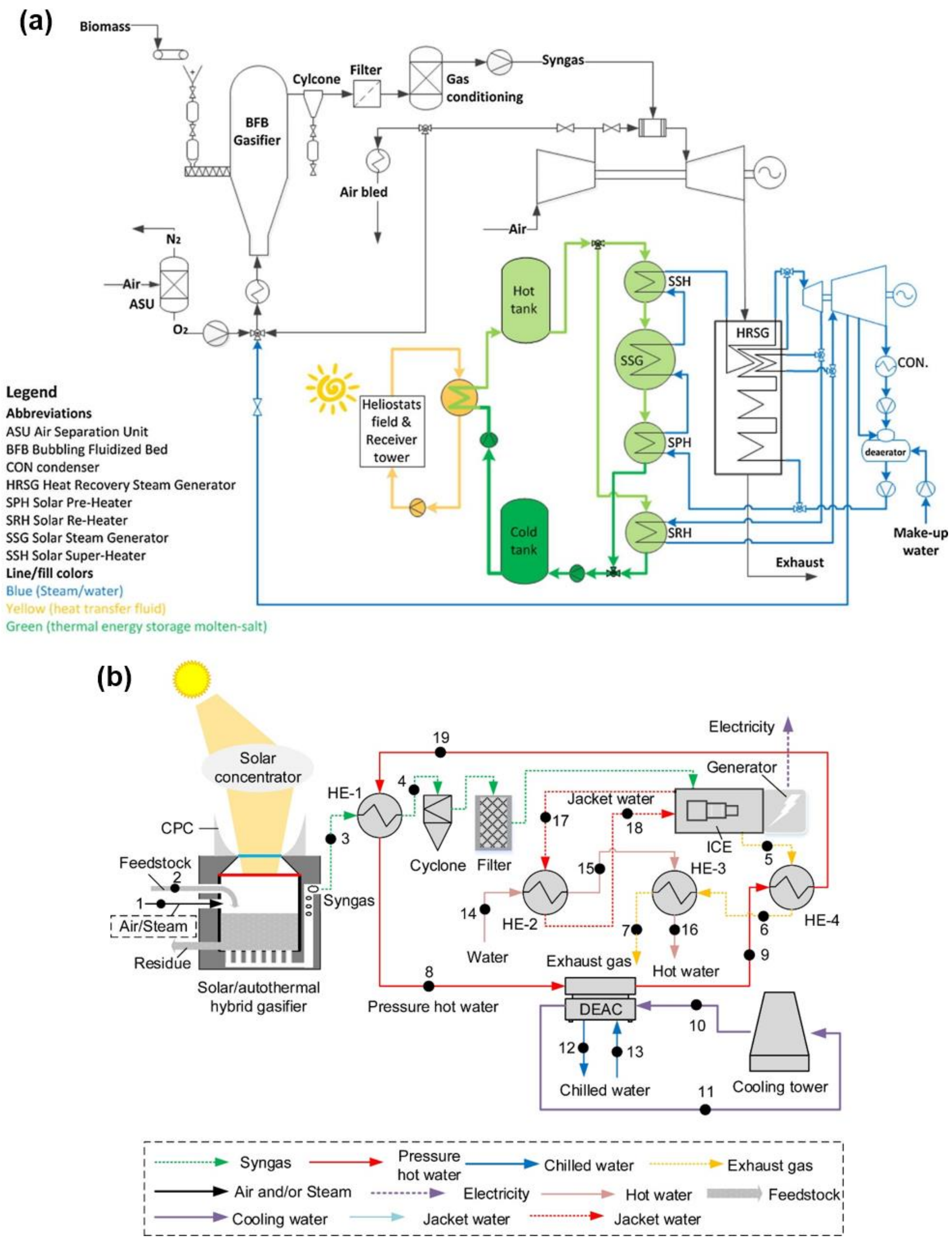

Fig. 2. (a) Schematic diagram of a gasification/concentrated solar thermal energy integrated system (entry 1 in Table 2). Reprinted from Tanaka et al. [59], Copyright (2015), with permission from Elsevier; and (b) Schematic autothermal/solar thermal gasification system (entry 2 in Table 2). Abbreviations: CPC – compound parabolic collector; HE – heat exchanger; ICE – internal combustion engine; DEAC – direct evaporative air cooler. Reprinted from Li et al. [62], Copyright (2017), with permission from Elsevier.

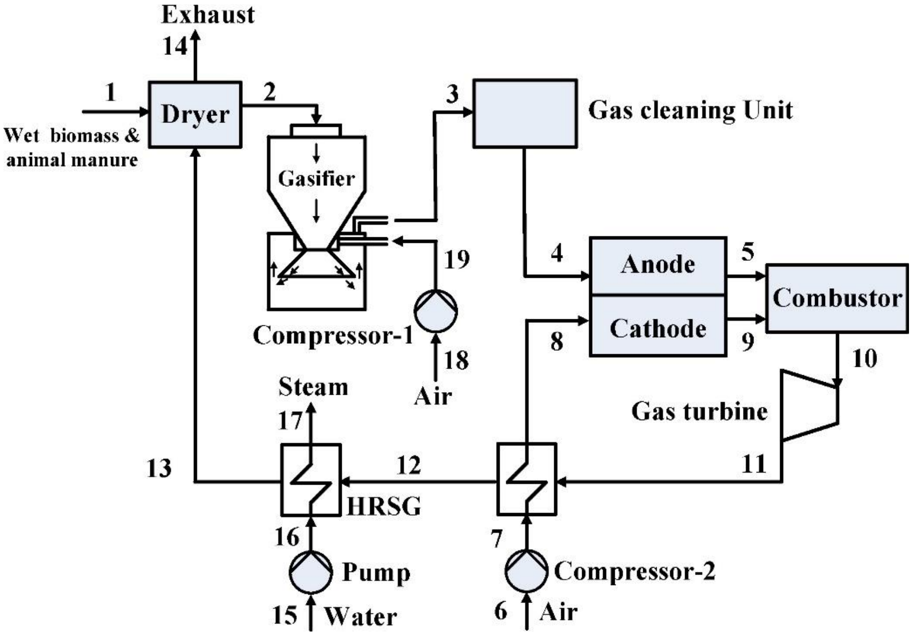

Fig. 3. Schematic diagram of a co-gasification/solid oxide fuel cell integrated system (entry 4 in Table 2). Reprinted from Jia et al. [77], Copyright (2018), with permission from Elsevier.

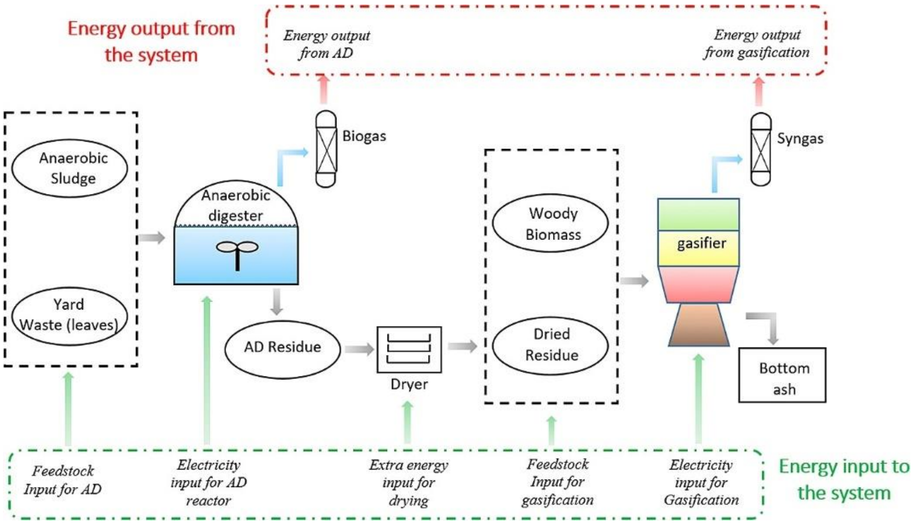

Fig. 4. Schematic diagram of an anaerobic digestion/co-gasification integrated system (entry 6 in Table 2). Reprinted from Yao et al. [80], Copyright (2017), with permission from Elsevier.

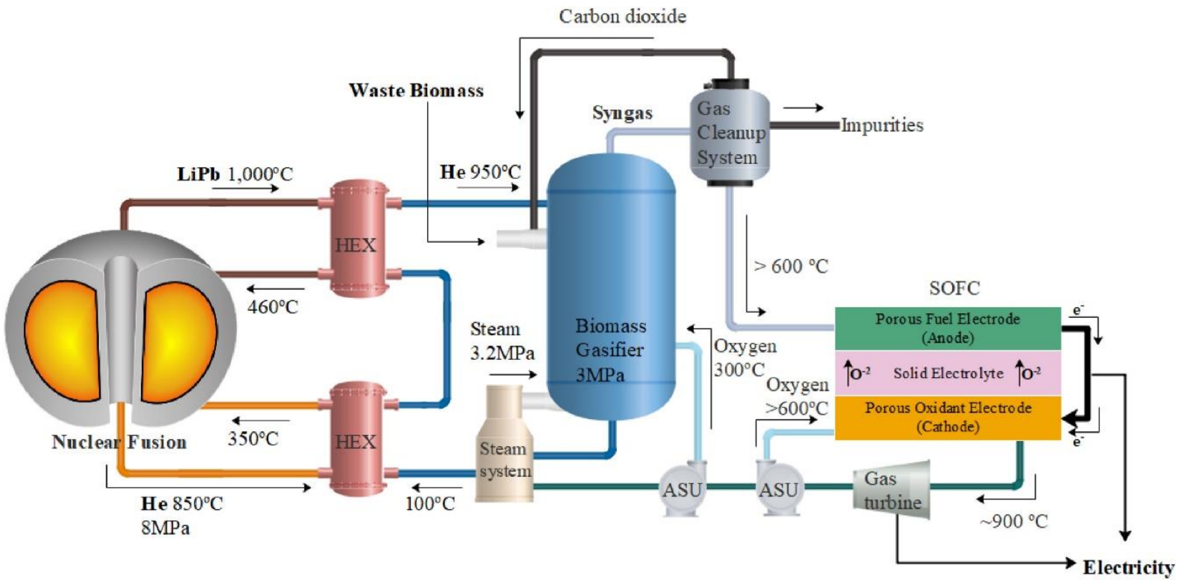

Fig. 5. Schematic diagram of a fusion/gasification/solid oxide fuel cell integrated system (entry 8 in Table 2). Abbreviations: He – helium; ASU – air separation unit. Reprinted from Nam et al. [83], Copyright (2020), with permission from Elsevier.

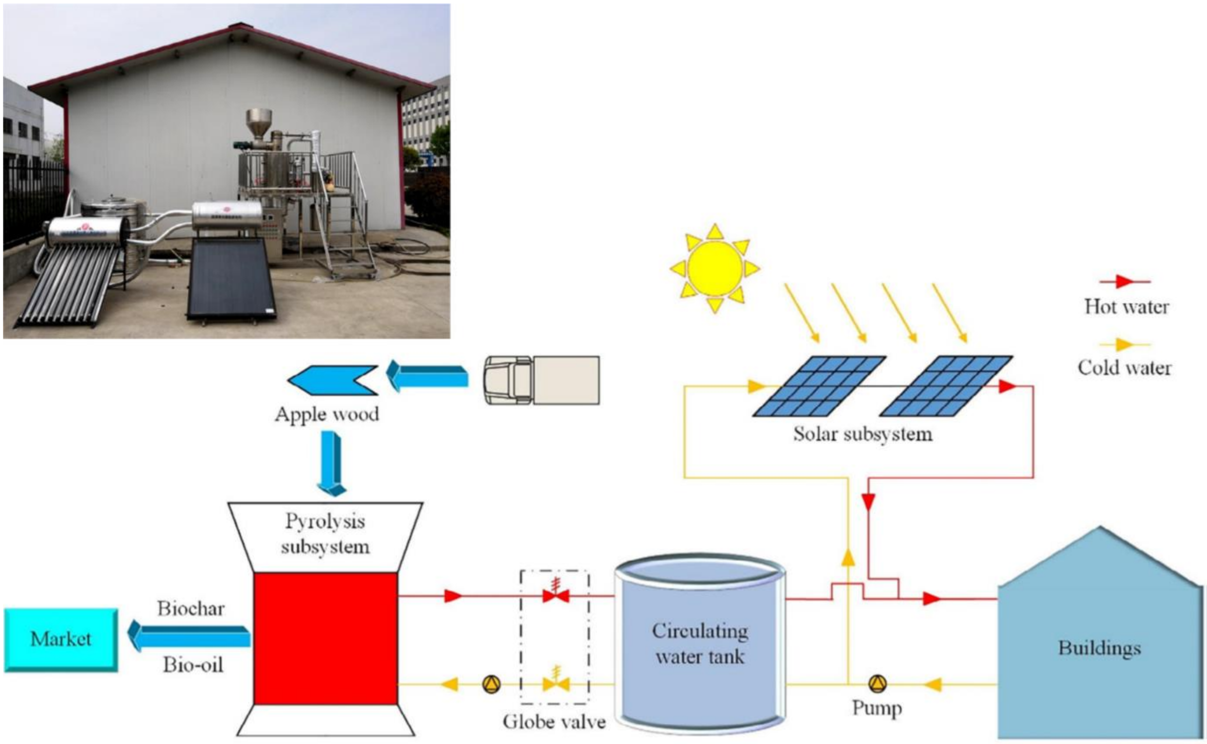

Fig. 6. Schematic diagram of a pyrolysis/solar energy integrated system (entry 1 in Table 3). Reprinted from Cheng et al. [87], Copyright (2019), with permission from John Wiley & Sons.

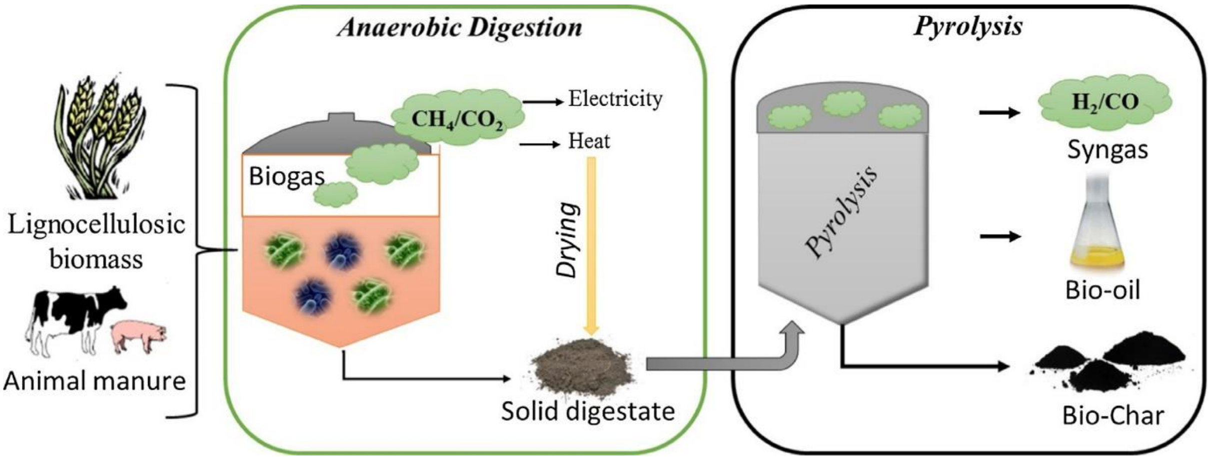

Fig. 7. Schematic diagram of an integrated system consisting of anaerobic digestion of lignocellulosic biomass/animal manure and pyrolysis of solid digestate resulting from the anaerobic digestion. Reprinted from Monlau et al. [89], Copyright (2015), with permission from Elsevier.

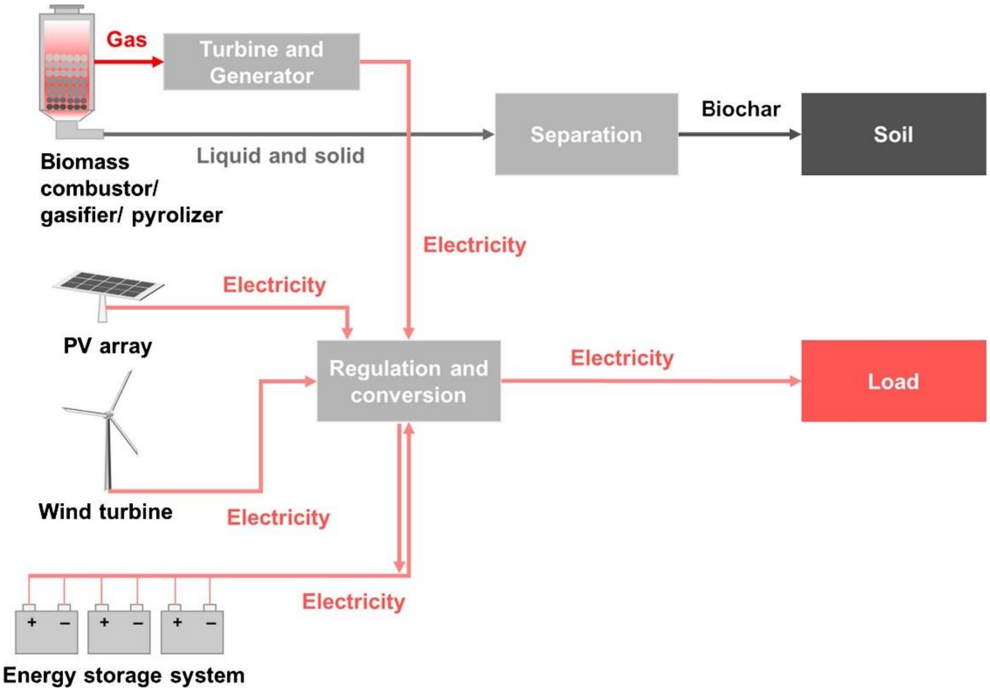

Fig. 8. Schematic diagram of an electricity generation/biochar production integrated system (entry 5 in Table 3). Reprinted from Li et al. [95], Copyright (2019), with permission from Elsevier.

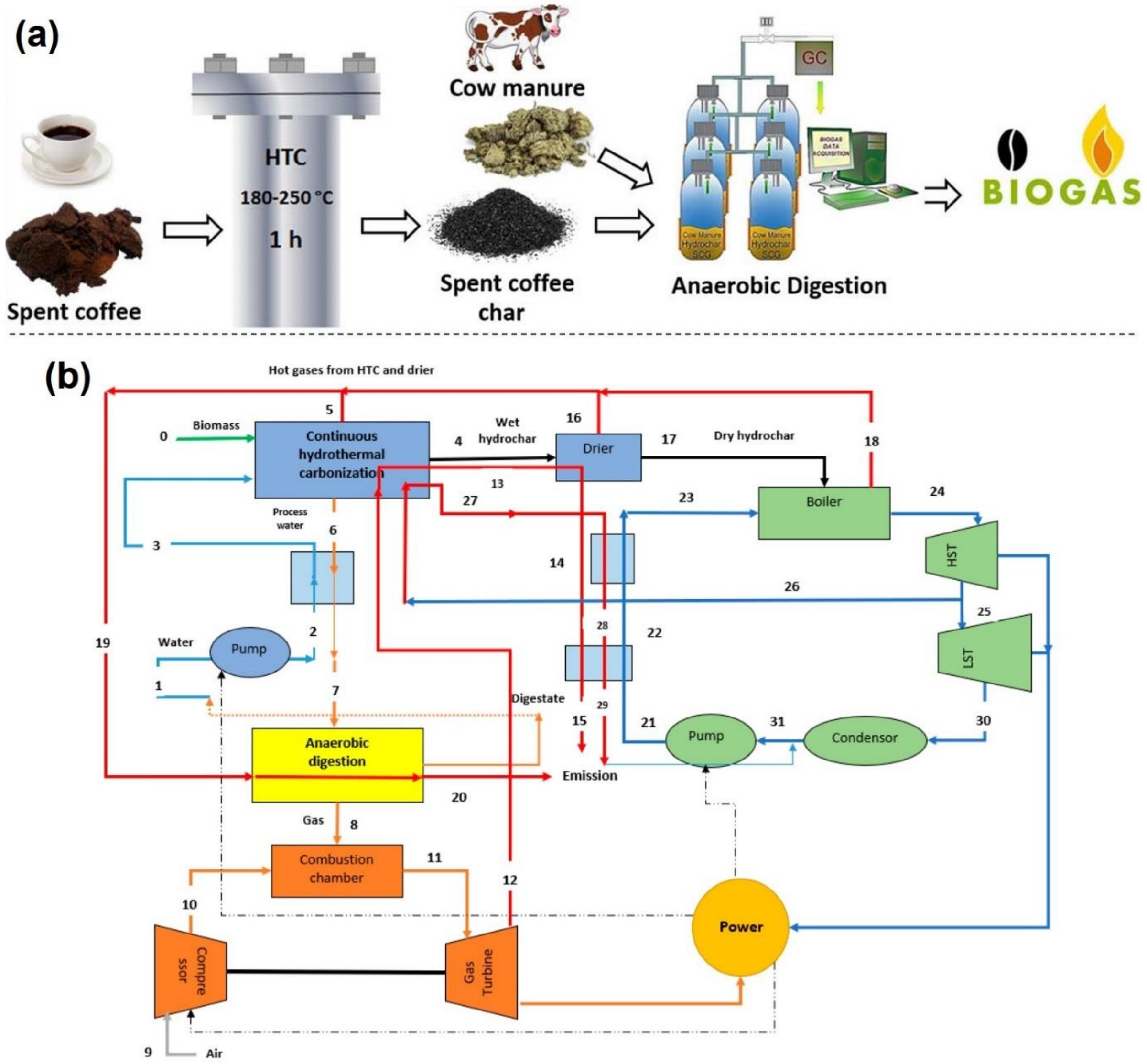

Fig. 9. (a) Schematic diagram of an integrated system consisting of hydrothermal carbonization of spent coffee ground and anaerobic digestion of the resultant char with cow manure for the production of CH_4 (entry 3 in Table 4). Reprinted from Codignole Luz et al. [101], Copyright (2018), with permission from Elsevier; and (b) Schematic diagram of a hydrothermal carbonization/anaerobic digestion integrated system for power generation (entry 4 in Table 4). Reprinted from Heidari et al. [102] and licensed under CC BY 4.0.