

The Emerging Role of Biomass in Complementing a Renewable Energy Portfolio: A Review

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Plant materials throughout the world, *i.e.* biomass, can provide annually roughly 18×10^{15} Watt-hours (6.5×10^{13} MJ) of energy, considering just the residues from agriculture and forestry. However, at least part of that amount has higher-valued uses, including being made into durable products, thereby keeping their carbon content from contributing to global warming. This review considers circumstances under which it may be advantageous to use biomass resources, either alone or in combination with other renewable energy technologies – such as solar and wind energy – to meet society's energy needs, especially for electricity, heating, and transportation. There is a rapidly expanding pool of published research in this area. To slow climate change, rapid maturation of the most promising technologies is needed, followed by their widespread and early implementation. Of particular interest are synergistic combinations of technologies, including the use of solar energy and biomass together in such a way as to provide hydrogen, heating, and electricity. Another need is to use biomass to make high-energy-density liquid fuels, including aviation fuels, diesel, and naphtha. Although some proposed schemes are complicated, biomass is expected to be gradually implemented as a growing component of installed renewable energy capacity in the coming years.

DOI: 10.15376/biores.20.3.Hubbe

Keywords: Pellets; Pyrolysis; Gasification; Combustion; Bioethanol; Biobutanol; Methane; Hydrogen

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Contents

Introduction	8024	Enzyme-based bioenergy	8047
Themes	8024	Overview of enzymatic systems.	8047
Hypotheses	8025	Anaerobic digestion	8047
Broader context	8025	Saccharification & fermentation.	8047
Intermittency	8031	Energy storage	8051
Energy source options	8032	Activated carbon to store energy	8051
Biomass as energy resource.	8035	Synergistic combinations	8052
Biomass energy overview.	8035	General issues of pairing	8052
Selecting types of biomass.	8036	Energy grid & hub systems	8052
Best uses of biomass	8037	Biomass & solar energy pairing.	8053
Thermal energy technologies.	8038	Biomass & wind energy pairing.	8055
Direct combustion options.	8038	Biomass, solar, & wind systems.	8055
Pellets and briquettes	8040	Biomass & geothermal pairing.	8056
Pyrolysis	8040	Enhanced biomass using solar.	8056
Hydrothermal conversion	8045	Environmental Impacts	8057
Pulping technology & energy.	8046	Technoeconomic analysis	8062
Biodiesel	8046	Conclusions	8063

INTRODUCTION

This review article considers broad questions related to what are the best roles for lignocellulosic biomass when planning how to meet society's future needs for energy. Because trees, agricultural residues, and other plant materials are expected to renew themselves continually as a result of photosynthesis and regrowth, it is logical to use the term "renewable" to describe this source of energy. In this work, the term energy will be used to denote not only electrical energy, but also thermal energy and various fuels that can be used on demand *via* their combustion in boilers or engines. However, biomass can be regarded as either competing with or complementing other promising renewable energy technologies, including hydroelectric, wind, solar, and geothermal. Therefore, it can be important to understand when it is appropriate to use biomass energy, when to use other renewable energy technologies, and when it might be appropriate to use two or more of these technologies in combination.

Themes

One of the most important issues considered in this article is the importance of integrating different renewable energy technologies in a synergistic way. For example, although the harvesting of wind energy is cost-effective and generally has a low environmental impact, its availability is intermittent (Abd El-Sattar *et al.* 2021). Likewise, solar energy is highly promising, but it is available only during the daytime and it becomes difficult to implement in regions where solar hours are low during the winter seasons. Meanwhile, installed hydroelectric generating facilities can be very cost-effective and reliable, but the available resources are limited and region-specific. By contrast, biomass is very widely distributed, and it can be used on-demand to create a combination of heating, steam, and electric power, as well as some other options, such as biomass pellets and liquid fuels. For example, an energy system based on combustion of biomass pellets can be started and run during periods of darkness or lack of wind.

Another theme that emerges from reviewing the literature is that although biomass is widely available, the resource is not unlimited, and its excessive usage can have adverse environmental and societal consequences. For example, it is important to focus on residues and waste material and to avoid production schemes that interfere with food production in an effort to meet energy needs (Muscat *et al.* 2020). From an environmental standpoint, one of the best uses of lignocellulosic material is for long-term products, such as in wood-rich building construction. In this way, the carbon content remains sequestered, thus contributing to limiting carbon dioxide emissions and limiting global warming to 2°C above pre-industrial levels. Based on the above, the present discussion will assume that some of the most suitable biomass resources to be used for energy production will be currently underused agricultural residues, as well as some forestry residues, such as branches and bark. Such resources can be supplemented by purposefully grown "energy crops," such as switchgrass, bamboo, and other fast-growing species (Koçar and Civas 2013). At the same time, it makes sense for society to place an emphasis on energy-saving initiatives, including making industrial and transportation systems more energy-efficient, better insulation of buildings, and more effective recovery and usage of currently wasted heat energy.

Another theme from recent literature is that many of the most recommended systems for renewable energy generation are likely to be location specific. A well-known example is the major availability of hydroelectric energy along the Columbia River in the

US northwest. Likewise, wind energy is best implemented in certain locations; examples include locations with high wind speeds, typically found on open plains, hilltops, mountain passes, and certain coastal regions that allow for optimal turbine efficiency (Gil-Garcia *et al.* 2019). In the case of biomass-energy, a key issue is the cost of transportation of plant residues, which often have low packing density; therefore, there is an advantage of locating biomass-to-energy facilities not far from where the residues are being made available.

A final theme is climate change. The effects of continuous greenhouse gas emissions have become well known, with increasingly severe consequences affecting the future of civilization. While these issues can be addressed, at least in part, by implementing optimized renewable energy technologies, the usual pace of implementation will need to be accelerated. The usual pace of academic and industrial research will not be sufficient. Rather, the whole field of research will need to mature more quickly than has been usual in the past. The most promising concepts need to be tested and retested, not only in the laboratory, but also in pilot-scale facilities and in industrial plants. To make any of this happen, the merits of the most promising proposals need to be justified to the satisfaction of research funding organizations, industrialists, and the general public.

Hypotheses

A central question to be addressed in this article is, “What are the most advantageous roles of biomass for a renewable energy portfolio?” In considering this question, the following hypotheses are proposed, together with some cited literature that can provide background in each case:

1. Biomass energy is well suited for production of combined heat and electricity (Mahian *et al.* 2020).
2. Biomass can provide “peaking power” and satisfy the energy demand when other renewable energy inputs are not sufficient to meet demands in combined systems that also include solar and/or wind energy (Spiru 2023; Acen *et al.* 2024).
3. Certain systems that combine biomass gasification with solar energy and hydrogen and optional biomethane production represent a promising pathway towards a hydrogen-based energy economy (Buffi *et al.* 2022; Takeda *et al.* 2022; Acen *et al.* 2024; Chen *et al.* 2024a; Mia *et al.* 2024; Sari *et al.* 2024).
4. Biomass energy can play a critical role in transportation, including air transportation, due to a high energy to mass ratio of certain organic compounds that can be obtained (Palaniswamy *et al.* 2023; Peters *et al.* 2023; Bobadilla *et al.* 2024; Ribeiro and Pereira 2024; Shahabuddin *et al.* 2020).

Broader Context of Renewable Resources

The distinction between photosynthetically renewable and non-renewable combustible fuels is described pictorially in Fig. 1. This diagram assumes that all of the carbon dioxide emitted to the atmosphere by the combustion of plant material will be captured by the continuing growth of plants. Such an assumption may be equivalent to proposing that the amount of biomass, averaged over the world, will remain at about the same level in the future. Though biomass is commonly regarded as a renewable resource,

it is not known for certain whether worldwide photosynthesis will continue to keep pace with the amounts of carbon dioxide being generated by combustion of biomass.

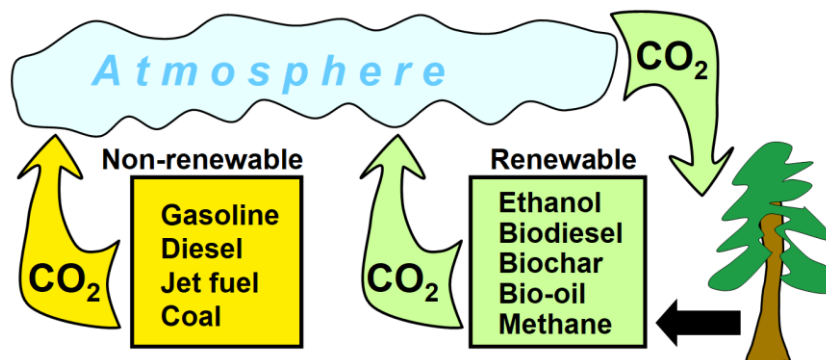


Fig. 1. Schematic contrast between different combustible fuels. Fossil fuels (at left) are regarded as non-renewable, since the produced carbon dioxide contributes to global warming. Bio-based fuels, as listed, are regarded as renewable because that carbon dioxide is assumed to be captured by the growth of biomass. The figure was inspired by artwork of Alper *et al.* (2020).

Estimates of some biomass resource quantities

To establish a suitable context for the discussion that will follow, the next step will be to estimate the relative amounts of different renewable energy resources that are presently available in the world, including the current levels of non-biomass renewable energy production capacities (Lal 2005). According to Bentsen *et al.* (2014), the annual amount of agricultural residues from the six most important crops in the world (namely barley, maize, rice, soybean, sugar cane, and wheat) is about 3.7×10^{15} g on a dry basis. Kim and Dale (2004) estimated a somewhat lower amount, 1.5×10^{15} g, for world residual biomass from seven crops (maize, barley, oats, rice, wheat, sorghum, and sugar cane). Deng *et al.* (2023) estimated the total world annual supply of biomass as 180×10^{15} g, but that number includes resources that would not be as easily available or practical for energy usage, compared to the residues from major crops. Gregg and Smith (2010) estimated the amount of forest residues available worldwide to be about 10.6% of the total of all biomass residues, including seven major agricultural crops. Based on a conversion factor reported by Nurek *et al.* (2019) for pine biomass, together with the factor estimated for biomass from Bentsen *et al.* (2014), the 10.6% value for biomass residues would correspond to roughly 0.4×10^{15} g/year. Related information limited to the US is available from the Center for Climate and Energy Solutions (<https://www.c2es.org/content/renewable-energy/>). To understand what these amounts could potentially mean in terms of energy, Table 1 uses the conversion factor determined by Nurek *et al.* (2019) for pine biomass.

Table 1. Estimates of Energy Generation Potential Based on Annual Amounts of Biomass in the World

Category	Biomass per year (dry grams)	Theoretical energy per year (Watt hours)	Citation
Agricultural residues	3.7×10^{15} g	16×10^{15}	Bentsen <i>et al.</i> 2014
“ “	1.5×10^{15} g	6.6×10^{15}	Kim & Dale 2004
Forestry residues	0.4×10^{15} g	1.8×10^{15}	Gregg & Smith 2010
Total biomass growth	180×10^{15} g	790×10^{15}	Deng <i>et al.</i> 2023

Note: The metric prefix corresponding to 10^{15} is peta.

Estimates of renewable energy contributions to the grid

Regarding the installed amounts of renewable energy capacity in the world, Fig. 2 shows that until recent years, almost all of the contribution to the electrical grid has been hydroelectric energy (Ritchie *et al.* 2024; see light blue colored areas in the figure). Since about 2000 there has been a considerable growth of wind (deep blue color) and solar energy (red) contributions, so that in 2024 those two energy alternatives comprise about 25% and 17% of the total, respectively. The “biomass and other” category in the figure (green), which according to Ritchie *et al.* (2024) is comprised almost entirely of biomass energy types, currently makes up about 8.5% of the total, *i.e.* about 0.8×10^{15} watt hours.

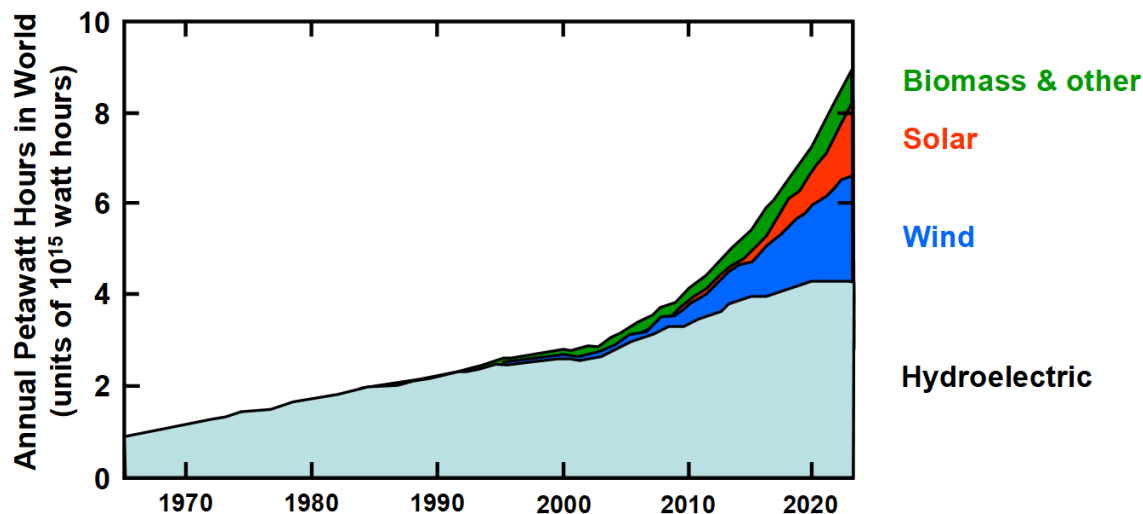


Fig. 2. Growth in worldwide contributions in the main renewable energy resources to the electrical grid from 1965 to the present. Plot redrawn based on an original from Ritchie *et al.* (2024)

By comparing Fig. 2 and Table 1, it becomes apparent that the current contribution of biomass to the worldwide electrical grid is only about one-tenth of the estimated renewables currently in usage. A current contribution of about 1 petawatt hour per year, which is the current contribution of biomass energy, is much less than the approximately 15 petawatt hours per year potential contribution of agricultural and forestry residues that was estimated based on the analysis of Bentsen *et al.* (2014). Thus, it would be theoretically possible to greatly increase the contribution of biomass to worldwide energy production (based on the electrical grid) just with the usage of agricultural residues.

Hydroelectric energy generation

According to Jennings (2016), hydroelectric power met about 6% of the world's electricity capacity requirements in 2015. Although hydroelectric energy can, in principle, be generated from tidal flows and waves, the main applications have involved the damming of rivers. The resulting reservoirs enable the water to build up a sufficiently high pressure (or “head”) so that it can generate power as it passes through a turbine. Although the concept is relatively simple, substantial engineering is required, including not only the construction of a dam, but also managing a new reservoir of water, including new flooded areas, as well as a generating station and transmission lines (Pereira 2021). Even though some hydroelectric plants are able to generate electricity throughout the

year, some others may change their output substantially, depending on the season and the amount of rainfall (Spiru 2023).

Although hydroelectric power generally can be regarded as having low environmental impact, relative to other major contributions to the electrical grid, installing a dam in a river immediately results in a large change in the aquatic habitat. For instance, the installation can be expected to adversely affect fish species that migrate, or which prefer fast-flowing water (Arantes *et al.* 2019). Other species that prefer lake environments may benefit. Thus, hydropower generation results not only in an environmental concern but also in a social impact, since ecosystems may be destroyed together with the displacement of settlements and loss of livelihood. Partial and involuntary resettlements of local communities are important social concerns to deal with during hydropower projects (Xu *et al.* 2011; Kaunda *et al.* 2012; Fearnside 2014; Moran *et al.* 2018).

Wind energy

Gil-Garcia *et al.* (2019) have used the terms “clean, ecological, and inexhaustible” to describe wind power. The main equipment consists of towers, rotors, electrical generators, and electrical transmission lines (Rivkin and Silk 2013). Wind energy shows potential as a clean and abundant energy source, whose main drawback is the variability and uncertainty of weather patterns. Some authors suggest the inclusion of energy storage systems such as batteries, pumped hydroelectric systems, or hydrogen generation to store excess wind power during high production periods and release it when needed. In this way it becomes a stable source of energy by integrating it into the electrical grid (Zhao *et al.* 2015). Extensive storage battery facilities as well as flexible use of hydropower or natural gas, are required to compensate for the variability of wind generation. Therefore, there would not be a complete substitution of energy but rather a mix of energy generation sources. Moreover, wind energy has notable land use requirements, implying various socioeconomic and environmental concerns (Rand and Hoen 2017). By including both off-shore and on-shore wind farms (*i.e.* multiple rotors in each case), there is a better chance that the wind by itself will be a substantial contribution throughout a typical week.

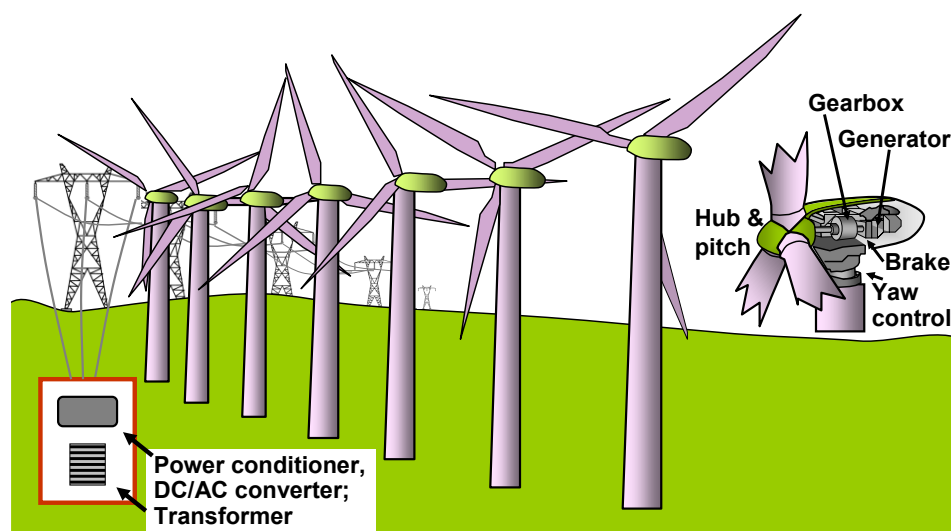


Fig. 3. Schematic diagram of a typical rotor system for commercial harvesting of wind energy

Commercial-type wind farm equipment allows for multiple adjustments that can maximize efficiency and improve durability (USDE 2024). For instance, the angle (pitch) of the rotor blades can be adjusted, depending on the wind speed, to keep the rotational speed within a favorable range. During a storm, when the operation of a rotor might lead to damage of the equipment, the blades can be rotated to a feathered condition such that the wind spills from the rotors without turning them. Figure 3 depicts a typical rotor system. Note that such systems have controls for such issues as facing toward the wind (yaw control), the angle of the rotor blades (pitch), and optional braking (Rivkin and Silk 2013). The generator, which is located next to the rotor assembly, may generate either direct or alternating current. Either within the base or adjacent to the wind tower or towers, the energy will be converted to alternating current (if necessary), conditioned, and transformed to a higher voltage, as needed for transmission or usage (Rivkin and Silk 2013).

According to Bonou *et al.* (2016), the most significant adverse environmental impacts of wind energy are those associated with construction, especially when building the heavy structures required for offshore wind farms. Some EPA reports indicate that although there are no direct emissions from the process of energy generation from wind, there are potential sources of pollution associated with turbine noise, visual impact, and potential harm to wildlife, particularly birds, in areas where wind farms are constructed; however, careful siting and design can significantly mitigate these problems (Wang and Wang 2015).

Photovoltaic solar energy

When considered for purposes of generating electricity, solar power installations come in several forms. Great progress has been achieved in recent years with respect to increased efficiency and reduced cost of photovoltaic systems (Hernández-Callejo *et al.* 2019; Singh 2013; Kumar *et al.* 2014; Ahmadi *et al.* 2018). Solar energy has become rapidly deployed. Units often are placed on the roofs of buildings or set up in rows on the ground. The key to this kind of energy production is the selection of a semiconductor layer with a suitable band gap, such that the incident light causes electrons to momentarily occupy higher energy levels, giving rise to a current (Kumar *et al.* 2014). Figure 4 shows a typical PV cell, which consists of n- and p-type semiconductors separated by a junction.

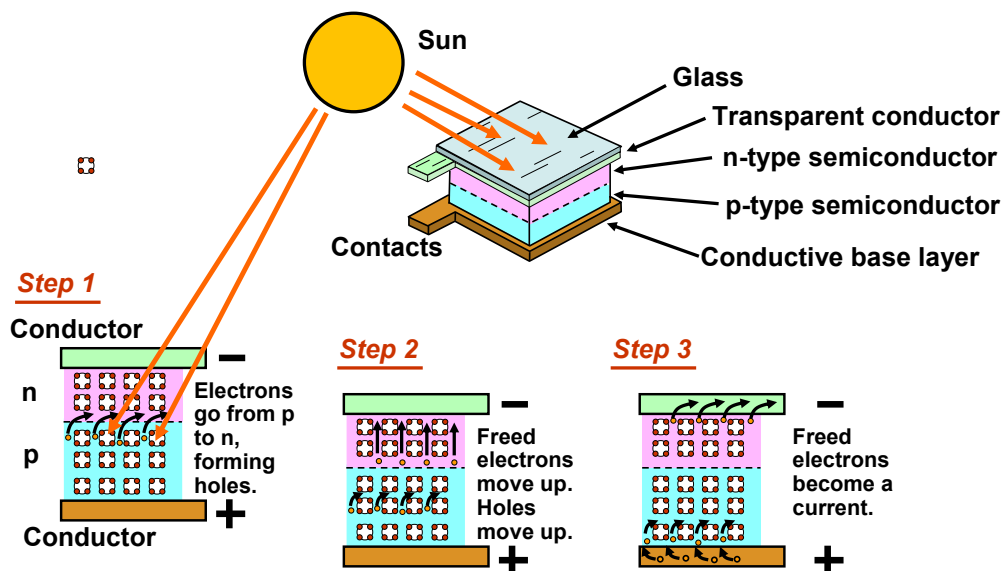


Fig. 4. Diagram of typical photovoltaic cell. Layers, starting from the bottom, will include a protective base structure, a conductor (+ pole), p-type semiconductor, junction, n-type semiconductor, conductor (- pole), and a glass window layer. The diagram is redrawn and simplified based on an original from the U.S. Energy Information Agency (2024).

In addition to a glass protective layer facing upwards, the system also includes a pair of conductive layers to harvest the produced current. Based on the review article by Muteri *et al.* (2020), the environmental impact of PV system manufacture, installation, and usage is complex, due to different materials of construction and different performance depending on the available light at different locations. Major contributors to environmental impact have been found to include semiconductor manufacture, and there is concern about depletion of certain elemental components of semiconductors. Kalogirou (2004), notes that some of the environmental benefits of solar energy are reduced emissions, no emission of air pollutants, reduced water consumption compared to gas and nuclear power plants, and greater energy independence. In addition, installation of PV solar energy collectors can span the range from powering tiny hand-held devices to involving large fields covered with solar panels.

Concentrated ray thermal solar energy

Besides photovoltaic systems, the other main technologies currently being used to capture solar energy are based on the concentration of the sun's rays and using the heat to drive a steam-based system for energy generation.

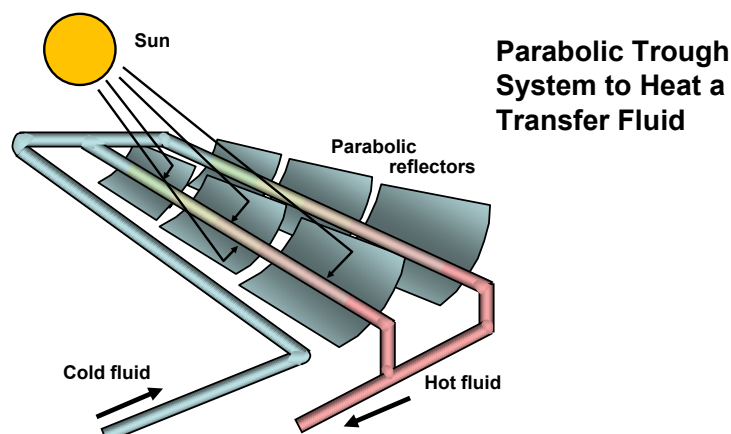


Fig. 5. Schematic diagram of parabolic trough system for collection of solar energy in the form of heat that can be used, for instance, in a steam turbine or steam engine

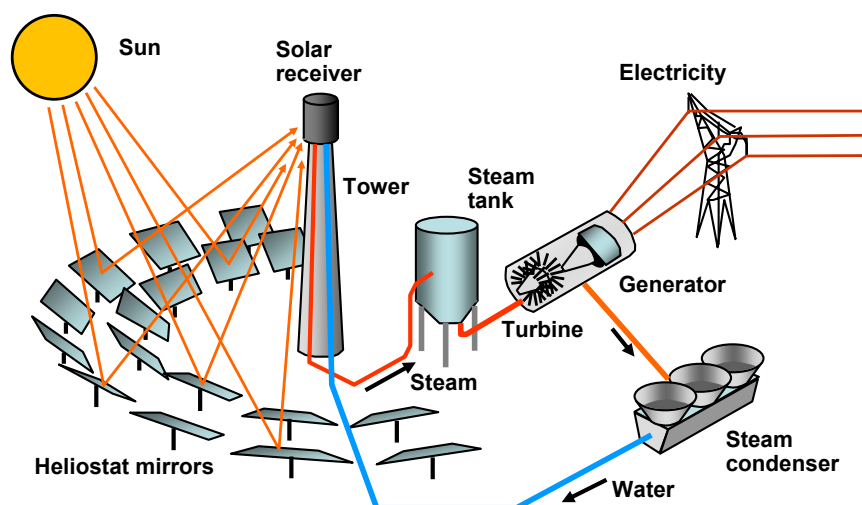


Fig. 6. Schematic diagram of heliostat tower system for collection of solar energy as heat

Figure 5 illustrates a parabolic trough system, which uses rotatable reflectors to aim the sun's rays onto tubing that contains a suitable fluid for transferring the heat to a steam-driven electric generator. In the case of a heliostat system, as illustrated in Fig. 6, mirrors in a field are programmed to change their direction depending on the sun's path across the sky, thus keeping the system near to its optimum focus on a tower (Ahmadi *et al.* 2018; Anaya-Reyer *et al.* 2024). Another approach uses Fresnel lenses to focus transmitted light on to a target heated surface, thus allowing for steam generation (Ahmadi *et al.* 2018; Ghasemi *et al.* 2024).

Intermittency of Renewable Energy as an Ongoing Challenge

Sceptics of certain renewable energy technologies, especially wind and solar installation, will point out their inherently intermittent nature. As already mentioned, the wind velocities at a given wind farm can be expected to be highly variable, including some periods of almost zero wind. Solar energy is generally more predictable, but no power is generated at night, much of the irradiation can be blocked by cloud cover, and the daylight hours, and angle of the sun are also dependent on the season. To illustrate the most rapid of such fluctuations, Fig. 7 shows some representative data for wind and solar energy generation for a 24-hour period (Abd El-Sattar *et al.* 2021).

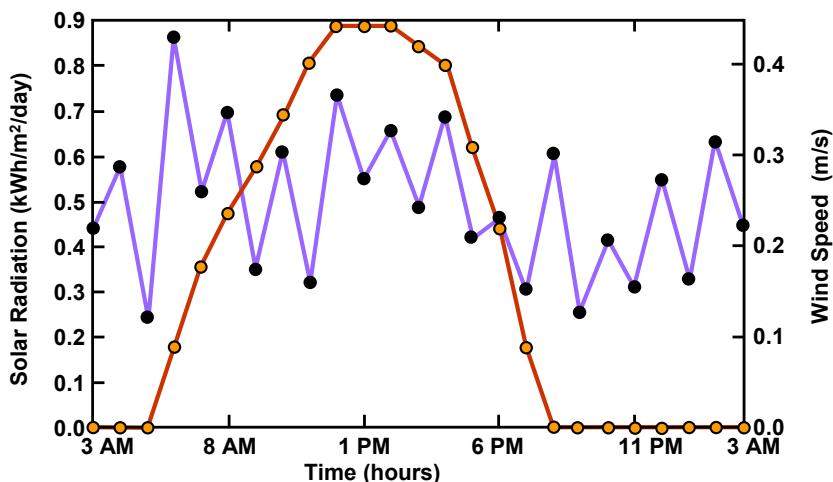


Fig. 7. Representative data from a study that considered possibly installations of (a) a wind energy farm; (b) a photovoltaic system for solar energy; and (c) a biomass-based energy generation system based on combustion. Here just the wind and solar data are shown for one of the days (redrawn based on Abd El-Sattar *et al.* (2021))

Though, in theory, problems of intermittency might be overcome by connecting wind and solar resources over very large geographical areas, one needs to be concerned about larger losses associated with longer average transmissions distances. Accordingly, the next subsection considers how such concerns might be addressed, at least in part, by various kinds of energy storage.

Energy Storage Options

Overview of energy storage

Energy storage involves trade-offs associated with multiple key factors such as energy density, power density, cost, lifetime, and environmental impact. These trade-offs can help reduce energy loss due to storage inefficiency in these systems. In addition, there will be costs associated with the installation and running of the needed equipment. Though conventional batteries can store energy, they are not the only option – especially when considering large amounts of energy. Other options include the pumping of water to a reservoir at a higher level, the compressing of air, or the rotation of flywheels. Sometimes it can be advantageous to store energy in the form of heat. Fuel cells can be regarded as serving the role of energy storage devices, with possible advantages in terms of efficiency. In addition, biomass itself is often regarded as a way to store solar energy, by a process of photosynthesis, such that it can be combusted later to produce heat and electricity (Bentsen and Moller 2017).

Regardless of the nature of the storage device, a great number of proposed designs of energy systems involving the use of renewable energy have also incorporated energy storage as part of the plan. Examples of these are listed in Table 2. Note that the “thermochemical” system described by Khudayar *et al.* (2004a) involves heating to melt salt, followed by storage of the liquid salt.

Table 2. Examples of Articles Proposing Energy Production Systems in Which Energy Storage Devices Help to Compensate for Variations in Generated Power

Type of Storage Device	Intermittent Energy Source(s)	Citation
Charging electric vehicles	Solar & wind	Mwasilu <i>et al.</i> 2014
Fuel cell	Solar (PV)	Singh & Baredar 2016
Water pumping & other	Various renewable energy sources	Gür 2018
Batteries (Pb)	Solar (PV) and wind	Malik <i>et al.</i> 2020
Charging electric vehicles	Solar (PV)	Tavakoli <i>et al.</i> 2020
Batteries (Pb)	Solar (PV) and wind	Pavankumar <i>et al.</i> 2021
Biomass fuel cells	(Biomass power generation)	Wang <i>et al.</i> 2021
Fuel cell (H ₂)	Solar (thermal)	Rajabi <i>et al.</i> 2022
Batteries (Li); flywheel	Solar (PV)	Akinte <i>et al.</i> 2023
Water pumping	Solar (PV) and wind	Menesy <i>et al.</i> 2023
Fuel cell (solid oxide)	Solar heat and power	Wang <i>et al.</i> 2023b
Batteries (Li & Pb)	Solar (PV) and wind	Youssef <i>et al.</i> 2023
Water pumping	Solar (PV)	Amusan <i>et al.</i> 2024
Thermochemical	Solar	Khudayar <i>et al.</i> 2024a,b
Fuel cells (high temp.)	Geothermal	Luo & Takhavi 2024
Fuel cell (H ₂)	Solar (PV) and wind	Modu <i>et al.</i> 2024
Batteries	Solar (PV) and wind	Zoladek <i>et al.</i> 2024
Batteries	Solar and wind	Chen <i>et al.</i> 2025

Notes: PV = photovoltaic

Battery options

The term “battery” was used in 1749 by Benjamin Franklin to describe a series of capacitors linked together to provide electricity storage (Sparkfun 2024). The definition reflects a key issue of importance when considering ways to store energy at its point of generation; even a household energy generation system would require a large number of individual electrical cells. Lithium batteries, which boast an especially high energy to mass ratio, have been used in some energy storage concepts for renewable energy (Perkins 2021; Wang *et al.* 2021; Akinte *et al.* 2023; Youssef *et al.* 2023). For example, it has been proposed to use the inherently variable wind energy for the recharging of electric vehicles, depending on the supply and demand cycles (Bamisile *et al.* 2020). Because solar and wind energies are mostly collected in fixed locations, and often connected to a grid, it is also feasible to use conventional lead-acid batteries, which are effective but much heavier (Malik *et al.* 2020; Youssef *et al.* 2023). The chemistries and emerging technologies of lithium batteries have been reviewed, with emphasis on their usage for storage of renewable energy (Hesse *et al.* 2017; Zubi *et al.* 2018). In addition, Xu *et al.* (2020) have reviewed emerging technology to increase the energy density in lithium batteries. An additional option, which is likely to decrease costs in future years, involves the development of sodium-ion batteries (Senthil and Lee 2021; Yan *et al.* 2022). Though all of these options appear promising, the fact that battery storage inherently requires a large number of cells tends to drive up costs. In addition, it should be noted that the production of these batteries involves the use of rare earths or minerals that generate harmful effects on the environment, mainly in the stages of extraction and final disposal of the equipment (Melchor-Martinez *et al.* 2021).

Water pumping with hydroelectric regeneration

Hydroelectric technology can offer a convenient way to store energy in locations where water can be pumped to a higher-level reservoir (Xiao *et al.* 2024). Such a system

has been proposed for the storage of solar energy (Amusan *et al.* 2023, 2024) and for solar-wind combination systems (Al-Ghussain *et al.* 2021; Menesy 2023). The technology can be regarded as mature and highly reliable. Truijen *et al.* (2024) estimated a round-trip efficiency of 67.5% for an improved energy storage system based on the pumping and hydroelectric regeneration of energy.

Air compression for energy storage

An alternative to the pumping of water involves the pumping of air into pressurized vessels. Such systems have been proposed for temporary storage of energy generated by wind or solar collection systems (Diyoke *et al.* 2018; Zhang *et al.* 2019b). The term adiabatic compressed air energy storage (A-CAES) has been used to describe such systems. An advantage of this approach is that the compressed air subsequently can be used to feed a biomass gasification process (Zhang *et al.* 2019b).

Flywheels for short-term energy storage

Flywheel technology appears well suited for relatively short-term smoothing of the energy fluctuations associated with various renewable energy generation systems (Akinte *et al.* 2023). In principle, such systems involve a rotating massive cylinder mounted on a low-friction axel, a reversible system of electrical power input and regeneration, and equipment for controlling and converting the electricity (Amiryar and Pullen 2017; Arani *et al.* 2017; Mousavi *et al.* 2017). According to Mousavi *et al.* (2017), the output gain for conversion between alternating and direct current for conventional flywheel technology can be no higher than 86.6%. However, a key concern for this kind of storage is the continual loss of energy over the course of time. For instance, Amiryar and Pullen (2017) proposed the range of 10 to 20% energy loss per day as an optimistic estimate for future installations.

Phase-change materials for heat storage

Another way to take advantage of periods of over-abundance of energy, such as when the sun is shining brightly or during strong winds, can involve heating up materials that need to be heated, but which are not particularly fussy regarding when the heating takes place. One such technology, which can contribute to the comfort of residences and office buildings, involves the use of phase-change materials. Kamaruzaman *et al.* (2024) proposed the use of heat storage in combination with a photovoltaic system and biomass gasification. In principle, the melting and subsequent re-freezing of such materials at a variety of different temperatures offers a way to capture and store the heat associated with the phase change. For instance, it has been proposed to use biomass-derived porous carbon materials as a carrier for selected phase-change compounds, having selected melting points (Jiang *et al.* 2022). Likewise, Li *et al.* (2022) impregnated wood with polyethylene glycol and its copolymer with maleic anhydride. By adjusting the ratio of these two components, it was possible to adjust the ranges of melting and refreezing. Tony (2020) describes usage of paraffin wax as a phase-change material, in combination with sugarcane bagasse as a structure to contain the wax.

Fuel cells as a means for more efficient energy storage

The term “fuel cell,” is commonly used to denote systems in which hydrogen, as well as some other energy-rich compounds, can be combusted, when needed, with the generation of energy (Sharaf and Orhan 2014; Manoharan *et al.* 2019). The products of

fuel cell operation can include electricity and heat. Wang *et al.* (2021) studied the potential usage of a hydrogen fuel cell system in combination with a pyrolysis system to convert biomass to energy. Rajabi *et al.* (2022) proposed usage of a fuel cell in combination with solar-assisted biomass processing to generate hydrogen and electrical energy. Unlike most other combustion processes, the product of the combustion of hydrogen within a fuel cell is water, rather than carbon dioxide. Thus, such technology has high prospects to be used in sustainable, low-pollution energy systems. Figure 8 provides a schematic diagram for a generic fuel cell.

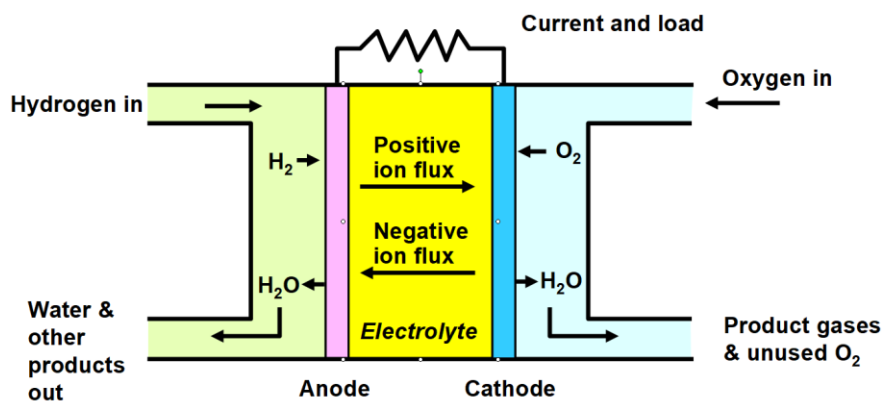


Fig. 8. Schematic diagram of a generic fuel cell. Figure redrawn based on an original from Manoharan *et al.* (2019)

BIOMASS AS AN ENERGY RESOURCE

Biomass Energy Overview

When industrialists decide to employ biomass as an energy source, several key decisions need to be made at the outset. As will be described in more detail later, technologies involved in the conversion of biomass to energy, including heat, steam, electricity, or portable fuels can be roughly categorized into thermal and enzymatic approaches. Both of these approaches ultimately work by converting the biomass into carbon dioxide, taking advantage of the energy of reaction. For instance, portable fuels such as ethanol are ultimately combusted to obtain their energy content at the point of use.

Biomass resources can be regarded as mixtures of chemical components, *i.e.* cellulose, hemicellulose, lignin, and often lesser amounts of ash and extractable components. This complexity means that developers of energy technology will need to make choices among different types of biomass, each of which will have some non-ideal behaviors. The thermal technologies mainly include direct combustion, pyrolysis (heating in the complete or major absence of oxygen), and also technologies in which pyrolysis is followed by other steps. For this type of process, a biomass with high calorific value and low moisture content could be beneficial. Conversely, enzymatic technologies have been used to prepare liquid fuels such as ethanol by saccharification and fermentation of the polysaccharide components (cellulose and hemicellulose) of the biomass.

In addition to a general approach of generating heat and electrical power, some potential applications of biomass may include replacement of fuels that are currently derived from fossil resources. However, according to the International Energy Agency

(IEA), an energy alternative is only attractive if it is possible to implement it using current systems and to ensure a long lifetime of the equipment. For this reason, the term “drop-in fuels” has been applied to cases in which the goal is to directly substitute conventional fuels with alternative fuels with chemically and functionally equivalent characteristics, compatible with the existing infrastructure (Dutta *et al.* 2023; Li *et al.* 2024; Subha *et al.* 2024). The allure of such applications stems from the potential usage of such fuels without having to modify the existing transportation infrastructure, thereby reducing the costs of implementation.

Selecting Suitable Types of Biomass for Energy Production

General considerations

Some factors affecting the type of biomass that may be the most suitable for bioenergy purposes include the availability, location, and season-dependence of the material. There may be important issues related to storage characteristics, low energy density, potential environmental impacts from large-scale cultivation, high moisture content, and aspects related to processing before use, which can increase production costs. In addition, there may be objectionable levels of inorganic compounds present within the material, which may give rise to ash accumulation or scale formation, depending on the technology that is employed.

Forest resources

A distinctive feature of wood-based resources, including stem-wood, branches, and bark, is the ability to harvest such material throughout the year. To gain the greatest value from wood resources, a stepwise progression is commonly employed. At the top, relatively large and straight stems of wood are often selected as sources of lumber. Residues from lumber production, including pieces too small to be made into lumber, or sections containing excessive knots or cracks can be advantageously used in such engineered products as oriented strand board or particleboard (Hua *et al.* 2022). After having exhausted those relatively higher-valued applications, which can lead to relatively long-term storage of the carbon content of the material, the remaining residue is often available for lower-valued uses, which can include immediate energy production (Thiffault *et al.* 2023) or densification of the material to facilitate its transportation, storage, and feeding to various furnaces.

Though the chemical composition of branch material is generally similar to that of stem material, current practices often leave that material to rot in the forest. The practical reason is that such materials tend to be bulky, which implies that many truckloads would be needed to bring them to a centralized processing facility.

Due to a lower content of cellulosic fibers, the bark component of trees is generally too weak for structural applications. In principle, bark could be used as a source of useful chemicals (Feng *et al.* 2013; Graf and Stappen 2022); however there has been relatively little implementation of such technology. Pulp and paper mills routinely remove bark from stem-wood in preparation for pulping of the wood. The bark component is routinely burned at the mill site for the generation of steam and electrical energy.

Agricultural residuals

Seasonal harvesting is a characteristic feature of agricultural residues, which means that residues obtained from the processing of crops also can be expected to be

available on an annual basis, depending on the crop (Ribeiro and Junior 2023; Sikiru *et al.* 2024). Another feature is that it is easy to predict both the location and the likely amounts of agricultural residues in future years (Roudneshin and Sosa 2024), whereas the cutting of forest resources is not bound by year or by season. Although different crops can have different seasons of harvesting, one of the inherent challenges when using agricultural residues for energy is the need to store the material for its later use. Alternatively, it may be necessary to plan for the use of different biomass resources during different seasons. This trend has already been reported by authors such as Piedrahita-Rodriguez *et al.* (2023), who claim that the use of multi-feedstock biorefineries can have many advantages, including environmental benefits, sustainable resource use, and economic benefits.

Some of the leading agricultural crops that yield a lot of residues after harvesting are corn, sugarcane bagasse, and soybean straw (Ashfaq *et al.* 2024). To this list, one can add wheat straw (Kumar and Vyas 2024) and rice stalk or husk (Mu *et al.* 2021). Some of these residues, such as rice residues, can contain substantial amounts of mineral content, such as silica. Although such mineral content can result in a lot of ash production during combustion, which has potential to interfere with some processes, various valuable end-uses have been found for the ash, which include concrete additive, bricks, and fillers for plastics and paints (Prasara-A and Gheewala 2017; Jittin *et al.* 2020).

Energy crops

Another promising source of biomass for use in energy production consists of purposefully grown crops, *i.e.* energy crops (Lewandowski *et al.* 2003; Koçar and Civas 2013). Examples include miscanthus, switchgrass, and sorghum. Such crops generally can be described as fast-growing, as well as not needing a lot of attention, in terms of fertilizers and pest control. Energy crops can have several advantages, including reduction of greenhouse gas emissions compared with fossil fuels, improving soil health, reducing erosion, and increasing soil organic matter.

Best Uses of Biomass in Terms of Energy Production: Overview

Another set of questions related to biomass and energy is “for what purpose”. For example, one might ask “What types of energy output are biomass resources best suited for?” Since many biomass resources are easily stored and can be burned when needed, one of the answers can be “for peaking power”. In other words, an electrical grid system can benefit if the system includes some energy sources that can be quickly put on line to meet peaks of energy demand – such as in the afternoon of a hot day, during which many air conditioners are running (Pérez-Navarro *et al.* 2010). Such a system can be configured to minimize costs and resources by relying more on wind and solar energies during periods of abundant supply of those resources (Abd El-Sattar *et al.* 2021).

Another line of questioning asks how the incorporation of biomass technology can amplify or enable what can be accomplished with other renewable energy installations. But before considering these questions, the sections that follow will first consider what can be done to enhance the usefulness and contribution of biomass itself as a renewable energy source. Thermal technologies will be considered first, followed by enzymatic technologies for biomass-to-energy processing.

ENERGY FROM BIOMASS: THERMAL TECHNOLOGIES

In broad terms, thermal technologies for obtaining fuels, steam, or electrical energy from biomass are related to combustion (*i.e.* burning in the presence of air or oxygen), pyrolysis (*i.e.* heating in the relative absence of oxygen), gasification (*i.e.* high temperature pyrolysis such that gases are the main product), hydrothermal liquefaction (*i.e.* using pressurize conditions to be able to carry out the transformation in liquid aqueous state), and technologies in which additional steps can be carried out at different levels of severity. This general area of technology has been reviewed by Chan *et al.* (2023), Ali *et al.* (2024a), and Jamil *et al.* (2024). Some thermal technologies that are important for biomass energy are discussed in the subsections that follow.

Direct Combustion Options

Domestic cooking and heating

There are two circumstances under which it can be advantageous to directly burn unprocessed biomass, with minimal attempts to control characteristics such as the moisture content, or to specify particle shapes, *etc.* One of these applications is household usage, for which the fuel may be collected by hand and fed directly to a furnace or oven to meet various cooking and heating needs. While this type of heating may make practical sense, especially when wood or other biomass sources are readily available close to where people are living, concerns have been raised regarding emissions (Olsen *et al.* 2020). Progress in the design of wood stoves has shown efficiencies above 80% (Carvalho *et al.* 2016), which represents a great advance relative to primitive fireplaces and rudimentary stoves. One of the keys to minimizing particulate emissions from such systems can involve automated control of air feeding. Practical considerations for improved efficiency and reduced smoke when using primitive wood stoves have been reviewed by Soini and Coe (2014). König *et al.* (2021) showed that the efficiency of such stoves can be markedly increased, and the particulate emissions reduced by a well-adjusted combination of exhaust and heat-exchanger fans, in addition to the use of a catalytic converter to promote complete combustion.

Hog fuel boilers for pulp and paper production

Another situation in which it can make sense to feed biomass to a combustion process with little or no preparation of the material is at the site of a pulp and paper production facility. Underutilized biomass in such cases may consist mainly of bark that had been removed prior to pulping operations, though it could also include branch-wood and knots. The term “hog fuel boiler” (Hubbe 2021) has been used for such equipment, which is illustrated in Fig. 9. A major concern with this type of boiler has been the likelihood of particulates, which can be minimized by increasing the efficiency and completeness of combustion (Huang *et al.* 2022).

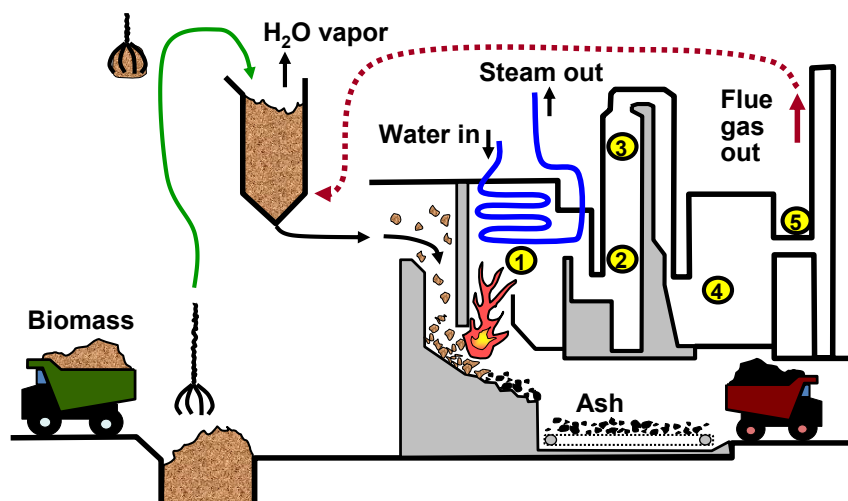


Fig. 9. Schematic diagram of combustion furnace for steam energy generation from biomass. Numbers refer to steps to mitigate fouling of the process equipment and to reduce harmful emissions, as described in the source document (Hubbe *et al.* 2021). Copyright owned by an author

Large-scale boilers for power generation

Biomass power generation is one of the most mature biomass utilization technologies. Biomass combustion, in particular, represents a critical pathway for low-carbon thermal power generation and commercial boiler applications (Wang *et al.* 2024b). Grate boilers and circulating fluidized bed (CFB) boilers are two primary technologies for biomass combustion. Of these, the CFB combustion (CFBC) technology offers superior fuel flexibility and lower costs for emission control; therefore, it has been widely adopted for biomass combustion (Yao *et al.* 2021). From 2019 to 2021, a Chinese manufacturer constructed 36 biomass CFB boilers, demonstrating the high demand for such equipment in industry for power generation (Ke *et al.* 2022).

In the early stages of CFBC development, biomass was typically co-fired with another solid fuel such as coal, which has a higher energy density, to maintain the stable operation (van den Broek *et al.* 1996). However, over the past 20 years, there has been an increasing number of plants performing direct biomass combustion in CFB boilers. At present, the largest direct biomass combustion CFB boiler has a capacity of 125 megawatts of electrical energy (Mwe), with steam pressure exceeding 9.8 MPa, and it achieves boiler efficiencies of over 90% (Ke *et al.* 2022).

However, several challenges remain in the commercial applications of direct biomass combustion, thus hindering the further improvements of biomass CFB boilers in terms of capacity, steam pressure, and steam temperature. One major issue is that biomass is usually of smaller particle sizes compared to coal. These fine particles have a higher tendency to escape from the cyclone separators and enter the flue tails as fly ash, thus negatively impacting the mass balance of the bed material in the main circulating loop (Yao *et al.* 2022). Moreover, biomass contains more alkali metal elements and chlorine. As such, Cl_2 and chlorides such as HCl , NaCl , and KCl , are released during combustion, resulting in severe corrosion of the heating surfaces (Chi *et al.* 2021). The presence of alkali metal elements in the biomass also lowers the ash melting points, exacerbating slagging and fouling issues during operation (Ma *et al.* 2025). Therefore, there is still considerable room to improve direct biomass combustion technology within

CFB systems. Further optimization of the cyclone performance and prevention of slagging, fouling, and corrosion of the metal heating surfaces are the key areas to improve the capacity and the steam parameters of the biomass CFB boiler for power generation.

Pellets and Briquettes

Densification processes are widely used in cases where biomass needs to be stored or shipped relatively long distances to a point of use. Pressing biomass into pellets (typically about 3 to 4 mm in diameter) or briquettes (typically about 4 to 12 mm in diameter) can be regarded as a relatively mature technology (Dinesha *et al.* 2019; Martin-Gamboa *et al.* 2020; Sarker *et al.* 2023; Ali *et al.* 2024a). The densified material is not only easier to ship and more efficient to store, but it also flows easily, as when it needs to be transported using conveyor belts, slides, or funnels (Sousa *et al.* 2024).

Torrefaction

To make biomass more suitable for various combustion or pyrolysis-related processes, it can be an advantage to treat biomass in the temperature range of about 200 to 300 °C (Olugbade and Ojo 2020; Chen *et al.* 2021; Sarker *et al.* 2021; Constantinou *et al.* 2024; Gizaw *et al.* 2024; Yang *et al.* 2024). Such treatment is sufficiently intense to start degrading the hemicellulose, thereby rendering the material less hydrophilic. As a consequence, the stored biomass will have a lower equilibrium moisture content, thereby increasing its effective heating value. In addition, the torrefied material can be easier to grind and form into pellets (Gizaw *et al.* 2024), except that the resulting pellets may be weaker. Abdulyekeen *et al.* (2021) evaluated the effects of torrefaction as a pretreatment of mixed solid waste as a way to enhance its fuel value. Torrefaction has been used as a pretreatment to enhance subsequent processes, such as gasification, resulting in a higher energy density, lower moisture content, and an overall reduction in volatile organic compounds (Liu *et al.* 2024a). As noted by Moscicki *et al.* (2014), torrefaction causes biomass to be more similar to coal, thus favoring its use as a coal substitute or partial replacement in the same boiler.

However, since torrefaction requires heat, rather than producing it, a good strategy may be to take advantage of waste heat, if available. For example, flue gas from a combustion process can be used for torrefaction (Yang *et al.* 2024). While such an approach can make sense theoretically, there is an inherent danger of unintended combustion due to the combination of flammable materials and high temperatures (Hubbe 2021). Even if oxygen has been excluded during the torrefaction process itself, the material could subsequently burst into flames due to inadequate cooling before release to the outside atmosphere.

As a possible alternative, with the potential to save energy of heating, it has been proposed to heat up moist biomass, without removing the moisture, in a process called wet torrefaction (He *et al.* 2018; Olugbade and Ojo 2020). As in the case of ordinary torrefaction, the process is expected to involve chemical changes, rendering the material more hydrophobic and having a lower equilibrium moisture content during storage.

Pyrolysis

The term pyrolysis can be broadly defined to cover a wide range of technologies. Starting at the lower temperature ranges, these technologies included biomass torrefaction, biochar production (converting much of the biomass to carbon), production

of a mixture of biochar and bio-oil, and finally gasification, at the high end of the pyrolysis temperature range. According to Constantinou *et al.* (2024), pyrolysis is generally understood to involve temperatures between 400 and 800 °C, whereas gasification often refers to processes operating in a range from 600 to 1300 °C. Because different temperatures can result in very different composition of the products, the subsections below will start from a lower range of treatment intensity and work upwards. It should be noted, however, that one of the characteristic features of pyrolysis in general is that a wide variety of products tend to be produced simultaneously. Review articles covering various topics in pyrolysis of biomass are listed in Table 3.

Table 3. Review Articles Covering Aspects of Biomass Pyrolysis

Focus of the Article	Citation
Thermochemical pyrolysis, with input for solar energy	Mondal <i>et al.</i> 2021
Thermochemical conversion with the goal of drop-in fuels	Kariim <i>et al.</i> 2022
Thermochemical processes leading to biorefinery to make fuels	Rodionova <i>et al.</i> 2022
Thermochemical conversion for renewable energy	Lee <i>et al.</i> 2023
Pyrolysis of biomass to make high quality fuels and chemicals	Zhang <i>et al.</i> 2023
Pyrolysis of agricultural residue biomass, including gasification	Ashfaq <i>et al.</i> 2024
Pyrolysis of waste biomass for power, heat, and biofuels	Begum <i>et al.</i> 2024
Pyrolysis with the goal of making solid, liquid, and gaseous fuels	Constantinou <i>et al.</i> 2024
Pyrolysis and hydrothermal treatments with biochar as a goal	Sharma <i>et al.</i> 2024

Pyrolysis for biochar production

A moderate pyrolysis treatment can be expected to yield a high proportion of biochar, along with some bio-oil in a typical temperature range between 350 and 700 °C (Nanda *et al.* 2016; Lee *et al.* 2020).

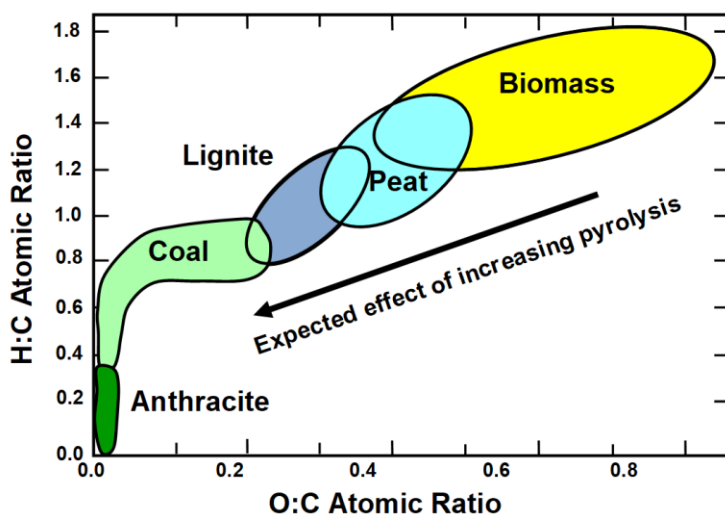


Fig. 10. A van Krevelen diagram, representing expected effects of increasing severity of torrefaction and pyrolysis of a typical biomass material. Figure reused, in slightly modified form, from Hubbe (2021)

Having a carbon-rich composition, biochar can be compared to coal. In fact, while some coal resources contain problematic amounts of sulfur, biochar is often very low in sulfur, which can be considered as an advantage – along with its pedigree of having been produced from renewable resources. To provide some context, Fig. 10 shows a “van

Krevelen” diagram, in which the atomic ratio of H/C on the vertical axis is plotted as a function of the ratio of O/C (Abdulyekeen *et al.* 2021; Chen *et al.* 2021; Hubbe 2021). In this diagram the most valuable fuel, represented by high-quality anthracite coal, occupies a space nearest to the origin, where the elements H and O are both very low. As shown, increasing severity of torrefaction of raw biomass makes it more similar to peat, and then more similar to lignite. Further pyrolysis, for biochar production, can be expected to yield a composition yet more similar to high-quality coal.

The temperature of processing can affect the resulting properties of biochar. In general, a higher temperature (but no higher than 700 °C) can be expected to increase the porosity and surface area, decrease the volatile matter, and change the chemical structure, but to decrease the yield (Nanda *et al.* 2016).

Pyrolysis for bio-oil production

An intermediate level of pyrolysis with temperatures between 400 and 650 °C, which is above what is optimal for biochar production, will increase the amount of bio-oil, which has potential to serve as a source of high-energy-density fuels and other organic monomers. Fast pyrolysis has been recommended as a preferred version of the process to maximize the amount of bio-oil relative to other products (Pan *et al.* 2024). Khudayar *et al.* (2024b) evaluated a system in which solar energy was used to power the pyrolysis process, converting biomass to bio-oil. In this way, it is possible to store solar energy in the form of the produced oil. However, for the product to be useful, it needs to be upgraded. As noted by Pan *et al.* (2024), crude bio-oil will contain water and a range of highly oxygenated compounds. The oil will be acidic in nature, corrosive, unstable, and not high in energy content.

Catalysts can be a key to upgrading bio-oil and facilitating conversion to a more preferred mixture of compounds (Kariim *et al.* 2022; Lesiak 2024; Subha *et al.* 2024). For example, the high surface area of zeolite can be used to convert the hot mixture to less oxygenated forms (Lesiak 2024). As an alternative, the needed catalyst to perform such transformations can be based on the waste biomass itself, in the form of biochar or activated carbon (Quevedo-Amador *et al.* 2024). An ongoing challenge associated with pyrolysis processes involves the fouling of equipment with tar, slag material, and other contaminants (Nelson *et al.* 2018). As noted in the cited work, catalytic processing of the gases can help to address those issues as well. Renugadevi and Maheswari (2022) advocated the use of thermal cracking to convert tar-like compounds to lower-mass species more suitable for use in fuels and in synthesis.

The term “biorefining” is often used to describe subsequent steps in the transformation of biomass-derived liquid compounds to more valuable compounds that can be used for fuels or for reagents in various chemical synthesis routes. For example, Fang *et al.* (2024) describe various specific reactions that can be used to convert biomass-derived compounds into suitable components for jet fuels. Okolie *et al.* (2021) noted that the products may include such monomers as propylene, ethylene, succinic acid, maleic acid, phenols, and other aromatic compounds. Qiu *et al.* (2024) noted that the common products of biomass, namely levulinic acid and 5-hydroxymethylfurfural, can be catalytically transformed to higher-value liquid fuels and chemicals. According to Ribeiro and Pereira (2024), catalytic processes remain as some of the most promising routes for the upgrading of compounds to make products such as jet fuels, but many challenges remain. However, based on the frequency of recent publications, there appears to be even more interest recently in biomass gasification than in pyrolysis. Such interest

may be attributed to the fact that gasification often produces a readily usable gaseous fuel (syngas) that can be transported and used for electricity generation in a variety of applications, whereas pyrolysis produces primarily a liquid bio-oil that may require further processing and refinement before it can be used effectively. Gasification, which will be considered next, is often regarded as a more flexible and potentially efficient option for energy production, especially when considering large-scale applications (Ahmed and Gupta 2009).

Reforming and gasification

Biogas reforming and biomass gasification are two widely applied thermochemical processes for converting raw materials to value-added products. Depending on the reforming or gasification agents, the biogas reforming can be categorized into dry (CO₂) reforming and steam reforming, while biomass gasification can be categorized into air/oxygen gasification and/or steam gasification. The primary gaseous products from these processes consist of H₂, CO, CH₄, and CO₂. When air is employed as the gasification agent, a large amount of N₂ will also be present in the product. Following separation and purification, the resulting syngas can be used as gaseous fuels or be used as the feedstock to produce liquid hydrocarbon fuels or methanol *via* Fischer-Tropsch or methanol synthesis.

Both the biogas reforming and biomass gasification typically require high reaction temperatures to achieve satisfactory conversion rates. The temperature range of the biogas reforming and biomass gasification are about 700 to 950 °C and 600 to 1300 °C, respectively (Zhao *et al.* 2020; Constantinou *et al.* 2024). However, recent development of the catalysts and reaction technologies have enabled low-temperature (< 600 °C) biogas reforming, offering the potential for lower energy consumption. Table 4 lists the main topics covered in several recent review articles on the subject of biomass gasification.

Table 4. Review Articles Covering Aspects of Gasification of Biomass

Focus of the Article	Citation
Gasification with emphasis on biofuels production	Molino <i>et al.</i> 2018
Chemical looping treatment of syngas, with solar power assist	Mu <i>et al.</i> 2021
Gasification of biomass using different designs and H ₂ enrichment	Tezer <i>et al.</i> 2022
Coproduction of syngas and biochar, including technoeconomics	Guerrero <i>et al.</i> 2023
Gasification and hydrogen enrichment, as well as tar mitigation	Lanjekar <i>et al.</i> 2023
Strategies for hydrogen-rich production by specialize pyrolysis	Matamba <i>et al.</i> 2023
Gasification of biomass, catalysts, and water-gas shift reaction	Wang <i>et al.</i> 2023a
Biomass gasification integrated with fuel cell technology	Wang <i>et al.</i> 2023b
Looping combustion and gasification of biomass	Güleç & Okolie 2024
Comprehensive review of syngas and its optimization	Khilifi <i>et al.</i> 2024
System with torrefaction and solar energy for improved gasification	Liu <i>et al.</i> 2024a
Membrane enrichment of H ₂ in syngas and other upgrade strategies	Meena & Pal 2024
Chemical looping treatment of syngas, with solar power assist	Mu <i>et al.</i> 2024
Biomass gasification, syngas cleaning, & technoeconomics	Sher <i>et al.</i> 2024

Hydrogen production

From the perspective of minimizing environmental impacts, there is worldwide interest in systems that maximize hydrogen production (Mortensen *et al.* 2020). For example, significant progress has been achieved in the direction of developing a carbon-neutral energy system (Denmark group 2024). However, >99% of the global hydrogen has been derived from fossil fuels (IEA, 2024), indicating that hydrogen production from renewable energy resources is urgently needed. Steam biogas reforming and steam biomass gasification are two promising technologies for green hydrogen production, offering sustainable alternatives to traditional fossil fuel-based methods.

A key to maximizing the amount of hydrogen from biomass is the use of steam biogas reforming and steam biomass gasification systems that involve the water gas shift (WGS) reaction (Wang *et al.* 2023a):



This reaction takes advantage of the fact that carbon monoxide, a major product of gasification, can be readily converted to hydrogen, which is more desirable. Although CO₂ from WGS is typically removed in a separate step, there has been an increasing interest in removing the carbon dioxide *in-situ* (Gao *et al.* 2019), *via* a process of sorption-enhanced steam reforming and gasification. The significant reduction of CO₂ partial pressure shifts the equilibrium of the water gas shift reaction, boosting CO conversion and enhancing hydrogen production. In particular, alkaline-earth metal oxides such as CaO, MgO, and SrO have been used as sorbents to capture the CO₂ (Florin and Harris 2008; Ramkumar and Fan 2010). However, those sorbents suffer from deactivation and require large temperature swings between carbonation and decarbonation steps, leading to additional cost and energy penalty to the system. Recently, perovskite oxides have emerged as a promising class of CO₂ sorbents for sorption-enhanced steam reforming and gasification under isothermal conditions, with CO₂ sorption and desorption triggered by redox reactions of the sorbent materials. Materials such as SrMnO₃, Sr_{1-x}Ca_xFe_{1-y}Co_yO_{3-δ} and Sr_{0.875}Ba_{0.125}MnO_{3-δ} have exhibited good cyclic stability and sorption capacity in isothermal steam biogas reforming and biomass gasification for producing green hydrogen or hydrogen-rich syngas (Cai *et al.* 2024, Rukh *et al.* 2024).

Other options include homogeneous and heterogeneous amines and sorbents. For hydrogen purification, the best-known approaches include use of a hydrogen-selective membrane and Pressure Swing Adsorption (PSA) technology (Gao *et al.* 2019).

The water shift reaction can be enhanced by means of a so-called chemical looping process, which can be achieved by incorporation of suitable catalysts into the gasification process. A version of this process is illustrated in Fig. 11.

In addition to enabling the production of increased proportions of hydrogen during biogas reforming and biomass gasification, it has been shown that the water-gas shift reaction also can be employed for chemical synthesis, where the reducing power provided by the CO/H₂O couple has been exploited in fine chemical synthesis. Other applications include hydrogenation and other catalytic processes that require a reductive step for the turnover of the catalytic cycle (Ambrosi and Denmark 2016).

To lead into the next subsection, involving hydrothermal treatment, it is important to note that gasification can be carried out under widely different conditions, as diagramed in Fig. 12 (Alper *et al.* 2020). When a biogas mixture is in a vapor state, catalysts can make it possible to break down higher-mass compounds at lower

temperatures than would otherwise be required, *i.e.* below 550 °C. In addition, the section of the diagram labeled as “liquefaction” defines conditions that are important for the next topic to be discussed.

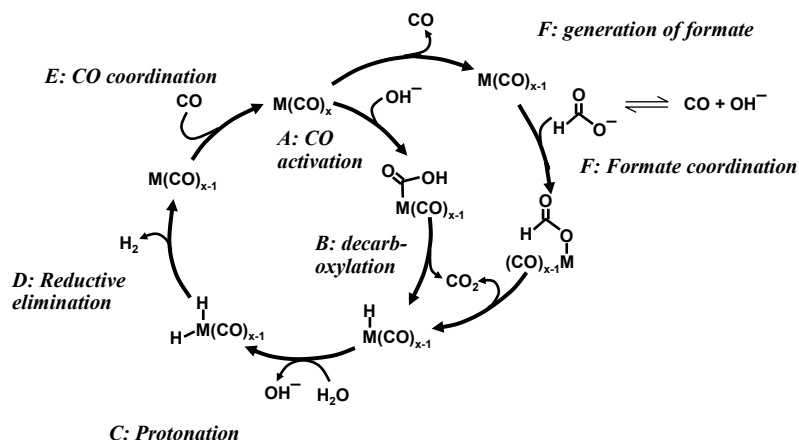


Fig. 11. Catalytic process for promoting the water shift reaction, in which a CO + H₂O mixture is converted into a CO₂ + H₂ mixture. Figure redrawn based on an original by Ambrosi and Denmark (2016)

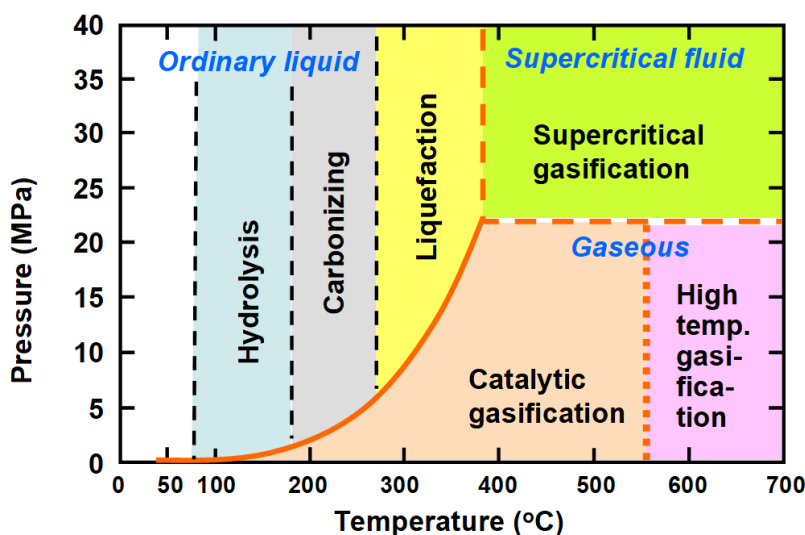


Fig. 12. Pressure-temperature diagram setting forth the conditions for different kinds of gasification, namely catalytic, high temperature (*i.e.* conventional), and supercritical. Figure redrawn based on Alper *et al.* (2020)

Hydrothermal Conversion and Liquefaction

Hydrothermal processes for biomass conversion into small molecules have been mentioned as a strategy by which to achieve effects similar to pyrolysis but with lower heating and without the requirement of evaporating the water. In fact, as the name implies, the water remains present and can participate in some of the reactions. Because the reactions take place under pressure, thus preventing vapor formation, the term hydrothermal liquefaction can be used (Alper *et al.* 2020; Grande *et al.* 2021; Perkins 2021; Shahbeik *et al.* 2023; Qiu *et al.* 2024). The main reactions start with the

depolymerization of the cellulose, hemicellulose, and lignin components of biomass, and then in the presence of catalysts, one can preferentially form high value fuels and chemicals from the intermediates, which may include levulinic acid and 5-hydroxymethylfurfural (Qiu *et al.* 2024). Shahbeik *et al.* (2023) found that higher bio-oil yields could be obtained within the ranges of 300 to 350 °C, with 24 to 26 MPa of applied pressure and 15 to 25 minutes of duration.

Pulping Technology and Energy Generation

One of the largest installed technologies for biomass conversion to energy consists of the recovery boilers that are used within the pulp and paper industry. These boilers are used to burn the lignin component obtained from the alkaline pulping of wood chips, and also to recover the pulping chemicals. The heat of combustion is used to produce steam, which is partly used to generate electricity and partly used to dry paper products in the mill. Energy recovery and efficiency issues related to pulping and papermaking were considered in an earlier review article (Hubbe 2021). The process is rendered challenging by the complicated nature of the spent pulping liquor (*i.e.* “black liquor”) that needs to be first concentrated by multi-effect evaporation and then incineration under a reducing atmosphere, capable of converting sulfate ions back to the sulfide form, which is one of the pulping chemicals. In some mills it can make sense to remove a portion of the lignin from concentrated black liquor by acidification (Hubbe *et al.* 2019) and thereby reducing the required boiler capacity to recover the pulping chemicals. In principle, it would be possible to burn the produced lignin as fuel, thus generating energy, but often the goal is to find higher value uses of the lignin.

Biodiesel

Biodiesel is another combustible fuel that can be made from biomass components (Garg *et al.* 2023; Damian *et al.* 2024). The main sources of biodiesel are vegetable oils, and there has been interest especially in the usage of waste cooking oil as a source of this product. Another source that could be considered consists of the fatty acids and triglyceride fats present in wood and algae. It has been proposed, for instance, to isolate wood components during the kraft recovery process, and then convert the material to biodiesel (Lee *et al.* 2006). In either case, the defining step is synthesis of the methyl esters of the fatty acids. This is mainly accomplished by catalytic reaction of methyl alcohol with the triglyceride fats (transesterification), giving rise to a mixture of long-chain alkyl methyl esters, glycerol, and highly alkaline water. The reaction is summarized in Fig. 13.

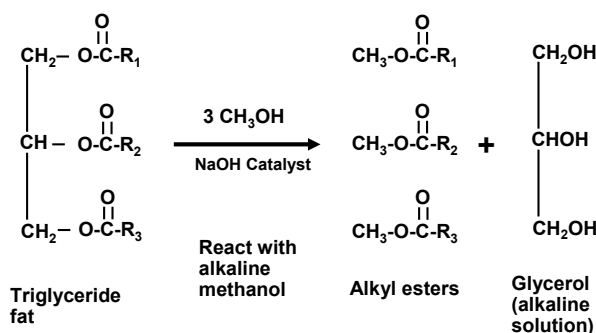


Fig. 13. Transesterification reaction to convert triglyceride fats (*e.g.* waste vegetable oils) to biodiesel by alkaline reaction with methanol

The use of alternative catalysts is a promising approach (Garg *et al.* 2023), which has potential to minimize the need for NaOH or KOH as a catalyst. Biodiesel, after its isolation, can be used directly in diesel-powered vehicles.

ENERGY FROM BIOMASS: ENZYME-BASED TECHNOLOGIES

Overview of Enzymatic Approaches to Bioenergy

Processes discussed in this section take place under mild conditions, including ambient pressure and temperatures no higher than about 70 °C. The upper limit of temperature is related to the rapidly decreasing periods of activity of the enzymes, which are the large proteins serving as catalysts for the needed reactions. Enzymes can be effective only when their peptide chains are folded in just the right way. Different enzymes have different tolerances for heating. Higher temperatures often can help speed up chemical processes, but eventually all of them will become denatured, meaning that they have lost their catalytic function. The two most interesting enzyme-based processes for preparing useful fuels products from biomass are anaerobic digestion and combinations of biomass saccharification and fermentation.

Anaerobic Digestion

Anaerobic digestion of biomass has been used especially as a way to treat wastewater, with methane being produced as a result of the process (Hubbe *et al.* 2016). In principle, much greater amounts of methane could be produced by anaerobically treating agricultural residues (Amjith and Bavanish 2022; Manikandan *et al.* 2023; Akter *et al.* 2024; Alengebawy *et al.* 2024; Ali *et al.* 2024b; Kumar and Vyas 2024). Although methane is typically the main product, conditions such as pH and temperature can be adjusted such as to favor hydrogen production (Bhatia *et al.* 2021; Buffi *et al.* 2022). Meena and Pal (2024) have reviewed technology for purification and concentration of methane after its anaerobic production, using such means as scrubbing, adsorption, cryogenics, and biological processes. While in principle the methane produced by anaerobic digestion can be utilized as a fuel or as a source for synthesizing other useful compounds, the managers of local wastewater treatment plants are likely to just burn it. The resulting CO₂ emitted has been estimated to contribute only about 2.7 to 3.6% of the global warming potential compared to skipping the combustion step and emitting the methane to the atmosphere (Derwent 2020; Mar *et al.* 2022).

Saccharification and Fermentation

In principle, the cellulose content present in residues from agriculture and forestry can be converted by enzymatic saccharification to glucose and by subsequent yeast-induced fermentation to ethyl alcohol (Ko and Lee 2018; Devi *et al.* 2021; Rodionova *et al.* 2022; Manikandan *et al.* 2023). By usage of suitable micro-organisms and their enzymes, it is possible to also hydrolyze the glycosidic bonds within hemicelluloses and to convert the resulting xyloses and hexoses to useful products, including ethanol (Chaudhary *et al.* 2023). However, it is well known that the rate of such transformations tends to be greatly impeded by the presence of lignin, as well as the relatively dense, intertwined structure of most unprocessed lignocellulosic biomass. Thus, the first step in an enzyme-based process leading to enzymatic saccharification and fermentation generally will be some form of pretreatment.

Pretreatment

A high-priority goal of various pretreatment strategies is to render cellulosic materials accessible to cellulase enzymes. This involves increasing the exposed surface area, keeping in mind that pores within the pretreated biomass will need to be large enough to allow passage of relatively large, folded proteinaceous structures. For instance, endoglucanases (a class of cellulase enzyme) have been reported to be about 4 to 6.5 nm in diameter and 18 to 21.5 nm in length, in some typical cases (Bubner *et al.* 2012). Some ways to open up the cellulose structure to favor access by such molecules include steam explosion, mechanical refining, and chemical treatments aimed at breakdown and removal of the lignin (Devi *et al.* 2021; El Hage *et al.* 2023; Bhat *et al.* 2024; Chopra *et al.* 2024).

Even in cases where pretreatment has exposed at least some of the cellulose to enzymes, lignin that remains in the material has potential to adversely affect rates of hydrolysis. Studies suggest that the relatively hydrophobic nature of lignin favors the unproductive binding and immobilization of cellulase enzymes, such that they are impeded in their work of breaking down the cellulose component (Wang *et al.* 2013; Fritz *et al.* 2015). Acid and alkaline pretreatments are the most popular ways to prepare lignocellulosic materials for bioethanol production. Alkaline pretreatment is more effective in lignin removal, while acid pretreatment is better in hemicellulose removal, depending on the specific biomass and the desired result. However, alkaline pretreatment is generally considered more favorable due to its milder conditions and less formation of inhibitory compounds such as furfural and HMF compared to acid pretreatment (Chaudhary *et al.* 2012).

Ethanol

Once the biomass has been pretreated, researchers and entrepreneurs can consider various general approaches to obtaining sugars and subsequent products such as ethanol (Bhatia *et al.* (2021). On the one hand they can first carry out the cellulose-catalyzed saccharification to form sugars and subsequently carry out fermentation in the presence of yeast to form ethanol. This option allows for separate optimization of the conditions for each of the two steps. Another approach is to carry out simultaneous saccharification and fermentation (SSF), in the same batch. This approach saves a step but involves compromises in terms of the operating conditions. Another challenge is to try to carry out the process with a minimum of water present; the goal is to minimize the amount of energy that is later needed to separate the ethanol from the water (Zhao *et al.* 2023). According to the cited review article, some of the potential problems with high-solids processing can include ineffectiveness of the pretreatment, formation of inhibitors, and high viscosity of the mixture. A third approach uses microbes to produce the enzymes during the SSF process (Bhatia *et al.* (2021). A fourth approach, aiming to avoid delays and to achieve higher yields, abandons the use of enzymes and relies instead on catalysts to achieve the same goals. The chemo-catalytic conversion of cellulose to ethanol is mainly achieved by catalytic cascade reactions involving cellulose hydrolysis, retro-aldol reaction, and hydrogenation, using multifunctional and bimetallic catalysts. However, problems with some catalysts or the use of toxic organic solvents limit their large-scale application. For this reason, future research could focus on the development of an efficient and environmentally friendly catalytic system that can significantly improve the ethanol yield with reduced cost (Gong *et al.* 2022).

Butanol

Compared to ethanol, butanol (especially 1-butanol and isobutanol) has more favorable properties as a potential drop-in fuel for gasoline (Fu *et al.* 2021; Vamsi Krishna *et al.* 2022). Thus, biobutanol can be considered as a replacement for bioethanol in fuel applications (Zhang *et al.* 2016). The most well-established production route to make butanol from biomass-derived pentose and hexose sugars involves acetone-butanol-ethanol (ABE) fermentation by anaerobic and solventogenic *Clostridium* spp. (Abo *et al.* 2019; Guo *et al.* 2022; Mahalingam *et al.* 2022). Four species, *C. butylicum*, *C. beijerinckii*, *C. saccharoperbutylacetonicum*, and *C. acetobutylicum*, are known to be highly effective 1-butanol-producing bacteria and are being utilized in industry and research (Nandhini *et al.* 2023). However, biobutanol production based on ABE fermentation still lacks technical and economic viability; this shortcoming has delayed the application of 1-butanol as a next-generation biofuel (Nabila *et al.* 2024). Considering the metabolic pathway during ABE fermentation, it is inevitable that acetone and ethanol are produced simultaneously, which suggests that 1-butanol selectivity is bound to be limited. The final product concentration in the broth, yield, and productivity of ABE fermentation are also known to be limited due to the higher toxicity of the accumulated 1-butanol (Abo *et al.* 2019).

Another drawback is the fact that the downstream process for 1-butanol recovery by distillation from the dilute fermentation broth (water) and from other solvent products is more complicated and costly than ethanol recovery (Jiménez-Bonilla *et al.* 2018). Various recovery techniques have been applied to avoid energy-intensive distillation from water (Rafieyan *et al.* 2024). Among them, *in situ* product recovery (ISPR) techniques can simultaneously recover the ABE solvent during fermentation, preventing toxic butanol accumulation in the fermentation broth. These steps allow the minimization of energy cost for solvent separation from water and increase the productivity and yield of ABE fermentation because of fermentation broth detoxification (Cai *et al.* 2022). Given the low productivity of 1-butanol production and the expensive recovery process, the application of an ABE mixture itself as biofuel has been attempted and actively studied for both gasoline spark ignition engines and diesel compression ignition engines (Veza *et al.* 2019). However, using an ABE mixture as a fuel component is not an ideal approach due to the poor fuel properties of acetone (Li *et al.* 2019). In this regard, metabolically engineered *Clostridium* spp. producing an isopropanol-butanol-ethanol (IBE) mixture instead of ABE mixture has been developed (dos Santos Vieira *et al.* 2019). Under IBE fermentation, acetone is not a final solvent product, and it is converted to isopropanol.

Until recently, isobutanol had not been recognized as a viable biofuel component, although it has similar or better fuel properties than 1-butanol (Chen and Liao 2016). This is because isobutanol is naturally produced in small quantities as a byproduct during ABE fermentation, and large-scale production has not been possible (Fu *et al.* 2021). However, intentional production of isobutanol recently has been achieved using *Escherichia coli* and *Saccharomyces cerevisiae* through metabolic engineering (Gu *et al.* 2021). Isobutanol fermentation also has the same process limitations of ABE fermentation, including by-products (ethanol and 2-methyl-1-butanol), toxicity by solvent accumulation, and energy-intensive solvent separation and purification (Fu *et al.* 2021).

Higher-value compounds and aviation fuels

Aviation fuel is a mixture of hydrocarbons (paraffins, isoparaffins, cycloparaffins, and aromatics) with appropriate carbon numbers (Liu *et al.* 2023). Given the highly

specified properties of aviation fuel, oxygen-containing fuel molecules such as bioethanol or biobutanol for gasoline or fatty acid methyl ester (FAME, biodiesel), which are suitable for diesel blends, are not suitable as fuel components for aviation fuel. In this regard, when it comes to fermentation, there are two main approaches to manufacturing hydrocarbons for synthetic aviation fuel or sustainable aviation fuel (SAF) (Walls and Rios-Solis 2020; Doménech *et al.* 2022; Goh *et al.* 2022). The first route is to produce terpenes such as isoprene, monoterpenes, or sesquiterpenes through microbial fermentation, followed by chemical upgrading to produce aviation fuel ranged hydrocarbons. The second route is to produce small oxygenates such as ethanol, 1-butanol, acetone, and isobutanol through microbial fermentation, then condense them to produce intermediates with appropriate carbon numbers, followed by chemical upgrading to produce aviation fuel ranged hydrocarbons.

Monoterpenes and sesquiterpenes are groups of terpene compounds with C₁₀ and C₁₅ carbon skeletons, respectively. In particular, monoterpene hydrocarbons and sesquiterpene hydrocarbons have the advantage of already having carbon numbers that can be used as aviation fuel, so they can be produced as aviation fuel components through metabolic engineering-based fermentation, followed by hydrogenation (Mendez-Perez *et al.* 2017; Woodroffe and Harvey 2020; Huang *et al.* 2023). One of the most well-known examples is farnesane (hydrogenated farnesene), which is known as “hydroprocessed fermented sugars to synthetic isoparaffin” (HFS-SIP). According to ASTM D7566, HFS-SIP was approved for blending at a 10% limit with conventional jet fuel in 2014 (Watson *et al.* 2024). Hydrogenated cyclic monoterpene hydrocarbons and sesquiterpene hydrocarbons are of interest as precursors for high-energy density aviation fuel components because of their high density due to the cyclic structure. Hitherto, various cyclic structures, including hydrogenated monocyclic and bicyclic monoterpenes (Woodroffe and Harvey 2020), hydrogenated monocyclic (Peralta-Yahya *et al.* 2011; Dai *et al.* 2021), bicyclic (Harvey *et al.* 2014), and tricyclic sesquiterpenes (Liu *et al.* 2018; Geiselman *et al.* 2020), have been studied based on metabolic engineering technology. Isoprene is also an important precursor for sustainable high-energy density aviation fuel (Wang *et al.* 2017; Isar *et al.* 2022). Cycloaddition of C₅ isoprene over designed catalysts, followed by hydrogenation, produces strained cycloparaffins in the aviation fuel range (Hu *et al.* 2024).

Although ethanol and butanol cannot be used directly as aviation fuel components, they are the most common small oxygenates used as precursors for alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK). After alcoholic fermentation, alcohol (ethanol or isobutanol) is converted to the corresponding alkene by dehydration. Longer alkenes are produced through controlled oligomerization from the short-chain alkenes (ethene or butene). Hydrogenation and subsequent distillation produce a mixture of paraffins and isoparaffins in the aviation fuel range (Geleynse *et al.* 2018; Goh *et al.* 2022). According to ASTM D7566, isobutanol-derived ATJ-SPK was approved for blending at a 30% limit with conventional jet fuel in 2016. Ethanol-derived ATJ-SPK was approved for a 50% blending limit in 2018 (Watson *et al.* 2024). Additionally, an ABE mixture can be employed to produce intermediate oxygenates with appropriate carbon numbers *via* alkylation of ketones with organic alcohols, self-condensation (Guerbet reaction) of alcohols, and oligomerization of ketones (Doménech *et al.* 2022). Long-chain hydrocarbons suitable for aviation fuels can be successfully produced from the intermediate oxygenates *via* hydrodeoxygenation.

Progress has been achieved in the development of specialized catalysts to enable the production of preferred organic compounds and fuels from biomass (Tosoni *et al.* 2023; Chen *et al.* 2024). These include single-atom metal catalysts, which have been reported as combining stability and efficiency. For example, Asikin-Mijan *et al.* (2021) performed an analysis on the efficient production of liquid and gaseous biofuels using monoatomic catalysts (SAC) and monoatomic alloys (SAA) in the reaction to promote it. SACs are formed by single metal atoms anchored or confined to a suitable support to keep them stable, while SAAs are materials generated by bi- and multi-metal complexes, where one of these metals is atomically distributed in the material. Thus, the inclusion of catalysts also expands the possibility of involving biomass as a precursor for current energy carriers.

It is possible to convert sugars produced from saccharification into more valuable compounds, including some suitable for aviation fuel, without the need for fermentation (Wang *et al.* 2020a; Okolie *et al.* 2021; Dutta *et al.* 2023; Peters *et al.* 2023; Fang *et al.* 2024; Quevedo-Amador *et al.* 2024). Bhatia *et al.* (2021) review primary synthesis pathways and processes that have been considered. Deng *et al.* (2023) and Ribeiro and Pereira (2024) outline catalytic processes based on transformation of sugars first to furfural and 5-hydroxymethyl furfural, and thereafter to such compounds as maleic anhydride and a wide variety of other compounds. Sarma *et al.* (2024) review the strategic co-culture of microbes to maximize biofuel production. Another approach to production of a diverse range of chemicals based on biomass involves photoelectric catalysis (Liu *et al.* 2024). Such processes can utilize the hydrogen resulting from the splitting of water to generate a mixture of compounds. Especially when considering ways to make a wide range of chemical compounds, starting with biomass, Begum *et al.* (2024) have urged developers not to overlook strategies that combine thermochemical and biological approaches in different phases of the processing.

ENERGY STORAGE, INCLUDING BY MEANS OF BIOMASS

Activated Carbon for Energy Applications

In addition to the various energy storage options outlined in the Introduction, there are some additional strategies that take advantage of the by-products from biomass. In particular, carbon products derived from the processing of biomass can be utilized as adsorbents for hydrogen storage or as supports for catalysts.

By pyrolytic treatment of either lignocellulosic material or biochar, especially in the presence of activating agents such as KOH or phosphoric acid, it is possible to achieve very high surface areas of carbon material, with a high population of pores having diameters of 2 nm or less (*i.e.* micropores). Activated carbon of this type can be optimized for the storage of hydrogen (Chen *et al.* 2024b; Wang *et al.* 2024). In this way, a product of pyrolysis has potential to enable relatively easy transport of hydrogen, which presently is a challenging aspect facing the widespread usage of hydrogen. Activated carbon also can be a component in sodium ion batteries (Yan *et al.* 2022). Another way in which carbon-based materials can contribute to the storage of energy is as components of supercapacitor systems. Carbon materials can serve as electrodes for such devices (Lin *et al.* 2021; Senthil and Lee 2021).

Finally, whereas catalytic approaches already have been mentioned in this review article, it is important to emphasize that products of biomass, especially activated carbon,

can serve as a support for certain catalysts (Kang *et al.* 2022; Chen *et al.* 2024b; Wang *et al.* 2024a). Some such catalysts even could be used in some of the processes already outlined in this article.

Biomass-based Components for Phase-change Energy Storage

Some options for the storage of energy were discussed earlier in this article. At this point it is worth noting that certain of those approaches can be based on lignocellulosic materials. These include using porous biocarbon (*e.g.* biochar) as a carrier for materials having melting points within a favorable range, such as room temperature (Jiang *et al.* 2022). Likewise, phase-change materials such as wax, which become liquid upon melting, can be held in place by being impregnated into wood (Li *et al.* 2022) or bagasse (Tony 2020).

SYNERGISTIC COMBINING OF RENEWABLE ENERGY SYSTEMS

General Issues in Pairing of Different Renewable Energy Systems

Having just considered various aspects related to effective use of biomass by itself as a source of renewable energy, this section will consider opportunities for simultaneous usage of such systems in combination with other renewable energy technologies such as wind, solar, and geothermal energy, as well as combinations of multiple technologies, along with storage options. A question to be considered, with respect to such combined systems, is whether there is substantial synergism. In particular, is there enough of an added benefit to justify the added complexity?

In preparation for such discussions, the next subsection considers issues related to the electrical grid. Besides considering the power grid in a broad sense, some of the same concepts can apply to isolated systems, maybe involving a small island, or even an individual household, *i.e.* a microgrid.

Energy Grid and Hub Systems

Electrical grids in general

Highly variable inputs of electricity, especially wind energy, are expected to place strains on existing electrical grid systems (Gür 2018). According to the source cited, increased storage capability can make a major contribution to addressing the problem. Currently a high proportion of energy storage systems on the grid are based on the pumping of water to higher elevations, thus enabling regeneration by conventional hydroelectric systems. As a precondition for major implementation of unsteady power inputs, there will need to be increased implementation of the kinds of storage systems that were outlined in Table 5. Substantial investment in such capacity will be needed. In addition, to minimize the need for large electricity flows in long-distance power lines, it is preferable to locate adequate energy storage systems close to the unsteady energy sources, *e.g.* solar and wind farms. In principle, smart grid technology can be implemented, so as to coordinate periods of high energy input – such as sunny and winding conditions – with the charging of electric vehicles (Mwasilu *et al.* 2014; Tavakoli *et al.* 2020) and other such demands that can be conveniently moved to off-peak demand periods.

Isolated systems

Many studies have been carried out related to grid systems for isolated communities or facilities, in which renewable energy was included in the design. Such studies can provide lessons that have potential to be applied more broadly, including their integration into the wider electrical grid. Table 5 mentions the focus of several such studies that have been published recently. Such work, to the extent that it truly tests the validity of the described systems, can help to support the general practicality of utilizing a grid to achieve a balanced supply and demand of energy from moment to moment.

Table 5. Studies Considering Microgrids and Isolated Systems with Renewable Energy Inputs, Including Biomass Energy

Focus of the Article	Citation
Grid analysis based on a Greek island with biomass and solar energy	Karellas & B. 2016
Grid with solar, fuel cell, biomass gasifier, and battery system	Singh & Baradar 2016
Grid for a zero-energy district in the city of Milan with solar (PV)	Aste <i>et al.</i> 2020
Rural grid for solar (PV), wind, and biomass gasification	Jahangir & C. 2020
Rural grid system with solar (PV), wind, biomass, and battery	Abd El-Sattar <i>et al.</i> 2021
Biomass usage to balance fluctuations in wind and solar (PV)	Al-Ghussain <i>et al.</i> 2021
Island energy system with solar (PV), wind, gasifier, and battery	Zoladek <i>et al.</i> 2022
Grid for solar (PV) with biomass generator and various storage units	Akinte <i>et al.</i> 2023
Isolated microgrids simulated with different algorithms	Ali <i>et al.</i> 2023
Solar (PV) & biomass integrated in a single building with microgrid	Behzadi <i>et al.</i> 2023
Grid evaluated for a town in Italy with hydro, solar, and biomass	Gul <i>et al.</i> 2023
Grid with solar (PV), wind, biomass, and water pumping storage	Menesy <i>et al.</i> 2023
Grid for city in Brazil with biomass gasifier using solar energy	Campos <i>et al.</i> 2024
Microgrid with solar (PV), wind, biomass gasifier, fuel cell, & battery	Modu <i>et al.</i> 2024
Solar (PV) and biomass boiler with floor heating and desalination	Zhu <i>et al.</i> 2024

Combining Biomass and Solar as Separate Units

Several studies have been carried out focusing on pairs of just two renewable technologies. In particular, there have been numerous studies involving integration of solar energy with biomass generation of energy. First to be considered are such studies that did not involve enhancement of the generation of hydrogen. These studies are listed in Table 6, with mention of the study focus areas. Among the reported benefits of such integration have been major reductions in the amount of biomass, as well as elimination of a need for energy storage (Altayib and Dincer 2022). Some studies took advantage of the high temperatures generated in the course of concentrated thermal solar energy technology to drive biomass gasification (Wang and Yang 2016; Calli *et al.* 2019; Koc *et al.* 2020; Palomba *et al.* 2020, 2021; Wu *et al.* 2020; Tsimpoukis *et al.* 2021; Altayib and Dincer 2022; Rajabi *et al.* 2022; Assareh *et al.* 2023; Anaya-Reyes *et al.* 2024; Ghasemi *et al.* 2024; Khadimallah *et al.* 2024; Khudayar *et al.* 2024a,b; Krarouch *et al.* 2024; Laleh *et al.* 2024; Mu *et al.* 2024). Several of the systems considered included Rankine cycles, which are based on idealized thermodynamic models of a steam engine. To put such a model into practice, heat is used to generate steam, which is run through a turbine and condensed.

Table 6. Studies Considering Integration of Solar Energy with Biomass Energy (without enhancement of hydrogen production)

Focus of the Article	Citation
Solar (PV) with biomass gasifier, fuel cell, & battery	Singh & Baredar 2016
Solar (PV) with biomass gasifier with modeling	Singh <i>et al.</i> 2016
Solar evacuated collector with biomass gasification and engine	Wang & Yang 2016
Solar & biomass with hydrogen production thermodynamic analysis	Yuksel & Ozturk 2016
Solar energy, biomass energy, and shared steam turbine	Anvari <i>et al.</i> 2019
Solar (parabolic trough) with biomass burner & Rankine cycle	Calli <i>et al.</i> 2019
Solar (PV) with gasification and internal combustion engine	Zhang <i>et al.</i> 2019a
Solar (PV) with biomass & groundwater heat pumps	Aste <i>et al.</i> 2020
Solar (PV) with biomass gasification & absorption cooling	Chattopadhyay & G. 2020
Solar dish with biomass gasification, turbine, liquefaction, <i>etc.</i>	Koc <i>et al.</i> 2020
Solar (PV) & biomass gasification with sustainability assessment	Li & Wang 2020
Solar thermal with biomass boiler & heat pulp for heating & cooling	Palomba <i>et al.</i> 2020
Solar dish to drive biomass gasification with steam	Wu <i>et al.</i> 2020
Solar thermal PV panels with biomass gasification and membrane	Cen <i>et al.</i> 2021
Solar options combined with biomass pyrolysis (review)	Mondal <i>et al.</i> 2021
Solar thermal with biomass boiler for heating, cooling, electricity	Palomba <i>et al.</i> 2021
Solar (PV) (or wind) with biomass pyrolysis and liquefaction	Perkins 2021
Solar (parabolic) with biomass gasification and turbine	Tsimpoukis <i>et al.</i> 2021
Solar thermal and biomass integrated for the heating of water	Altayib & Dincer 2022
Solar thermal with gasification and thermal energy storage	Rajabi <i>et al.</i> 2022
Solar (PV) with biomass gasification for natural gas & power	Wu <i>et al.</i> 2022
Solar with biomass energy for household heating thermodynamics	Zhang <i>et al.</i> 2022
Solar (PV) with biomass generator and various storage units	Akinte <i>et al.</i> 2023
Solar thermal, biomass, and hydrogen liquefaction with gas turbine	Assareh <i>et al.</i> 2023
Solar (PV) with novel biomass heater for a smart building	Behzadi <i>et al.</i> 2023
Solar (PV) with biomass generator and small hydroelectric plant	Ceglia <i>et al.</i> 2023
Solar, hydroelectric, & biomass model with switching algorithm	Gul <i>et al.</i> 2023
Solar with biomass gasification for hotel heating & power	Jie <i>et al.</i> 2023
Solar driven biomass gasification and turbine with preheating	Li <i>et al.</i> 2023
Solar energy with gasification to prepare fuels (review)	Xu <i>et al.</i> 2023
Solar (PV), biomass, diesel, and time of use integration for pumping	Amusan <i>et al.</i> 2024
Solar tower & geothermal Rankine cycle and biomass gasification	Anaya-Reyes <i>et al.</i> 2024
Solar (PV) biomass gasifier system for an academic building	Baghel <i>et al.</i> 2024
Solar (PV) with biomass gasification of <i>Eucalyptus</i> residues	Campos <i>et al.</i> 2024
Solar (Fresnel) with biomass solid waste, electrolysis, desalination	Ghasemi <i>et al.</i> 2024
Solar (PV) with pyrolysis, combustion, & gasification with algorithm	Irshad <i>et al.</i> 2024
Solar thermal PV with biomass gasification & phase change	Kamaruzaman <i>et al.</i> 2024
Solar thermal PV with biomass digester & heat pump	Karkon <i>et al.</i> 2025
Solar thermal with gasification of sewage waste after anaerobic	Khadimallah <i>et al.</i> 2024
Solar heliostat field with biomass pyrolysis and energy storage	Khudayar <i>et al.</i> 2024a
Solar heliostat field with biomass pyrolysis and energy storage	Khudayar <i>et al.</i> 2024b
Solar thermal with biomass pellet boiler & home heating	Krarouch <i>et al.</i> 2024
Solar thermal PV with biomass gasification & fresh water	Laleh <i>et al.</i> 2024
Solar with biomass torrefaction & gasification & refrigeration	Liu <i>et al.</i> 2024a
Solar thermal with biomass gasification & Rankine cycle	Mu <i>et al.</i> 2024
Solar with 2-stage biomass organic Rankine cycle & preheater	Qi <i>et al.</i> 2024
Solar with biomass gasification, Rankine cycle, and combustion	Sabbaghi & Sefid 2024

Table 7. Studies Considering Integration of Wind Energy with Biomass Energy

Focus of the Article	Citation
Wind with biomass gasification and gas storage & generation	Pérez-Navarro <i>et al.</i> 2010
Wind energy with biomass gasification and compressed air	Diyoke <i>et al.</i> 2018
Wind energy was modeled as an addition for existing gasification	Endrjukaite <i>et al.</i> 2019
Wind energy with biomass energy to cover shortfalls in wind	Tajeddin & Roohi 2019
Wind and biomass integration with dynamic & steady state analysis	Bamisile <i>et al.</i> 2020
Wind and biomass energy reviewed for biofuel production	Amjith & Bavanish 2022
Wind with biomass energy found advantageous for rural areas	Erdiwansyah <i>et al.</i> 2022
Wind and biomass energy for heating, electricity, and hydrogen	Acen <i>et al.</i> 2024

Biomass and Wind

Fewer studies have been focused on combining just wind power and biomass energy, and these are listed in Table 7. A general finding was that such hybrid systems can cover shortfalls in wind availability, while also decreasing the amount of biomass needed.

Biomass, Solar, and Wind

Although combining three different renewable systems will be inherently more complicated, it is reasonable to expect synergisms, for instance due to the ability to collect wind energy at night. In addition, once a microgrid has been set up, for instance, for a combination of wind and biomass energy, it can become easy to incorporate an additional variable input of energy to the system. Table 8 lists studies that considered such three-way combinations for energy generation. Storage systems were considered in a majority of these studies.

Table 8. Studies Considering Integration of Wind, Solar, and Biomass Energy

Focus of the Article	Citation
Solar (PV), wind, and biomass with storage and simulation	Singh <i>et al.</i> 2016
Solar (PV), wind turbines, and biomass gasification for electricity	Jahangir & Cheraghi 2020
Solar (PV), wind farm, biomass gasification system for a building	Malik <i>et al.</i> 2020
Solar (PV), wind farm, biomass, and battery storage	Abd El-Sattar <i>et al.</i> 2021
Solar (PV), wind, and biomass, minimizing need for storage	Al-Ghussain <i>et al.</i> 2021
Solar (PV), wind, and biomass and battery with algorithm analysis	Pavankumar <i>et al.</i> 2021
Solar (PV), wind, and biomass steam generation	Figaj <i>et al.</i> 2022
Solar (PV), wind, and biomass off-grid system with simulation	Hossen <i>et al.</i> 2022
Solar (PV), wind, and biomass with hydrogen and heating & hub	Nasir <i>et al.</i> 2022
Solar (PV), wind, and biomass gasification with fuel cell	Zoladek <i>et al.</i> 2022
Solar thermal, wind, biomass system from sludge simulated	Alhijazi <i>et al.</i> 2023
Solar (PV), wind, and biomass for water pumping	Amusan <i>et al.</i> 2023
Solar (PV), wind, and biomass with water pumping	Menesy <i>et al.</i> 2023
Solar (PV), wind and biomass with battery, simulated	Youssef <i>et al.</i> 2023
Solar (PV), wind, and biomass gasification with battery storage	Modu <i>et al.</i> 2024
Solar (PV), wind, and biomass with diesel and battery storage	Patil <i>et al.</i> 2024
Solar (PV), wind, and biomass gasification with hydrogen storage	Zoladek <i>et al.</i> 2024
Solar, wind, biomass with storage for heating, cooling, and power	Chen <i>et al.</i> 2025

Biomass and Geothermal

Because geothermal energy, similar to hydroelectric energy, tends to be quite stable as a function of time, there tends to be less motivation to combine it with another system, such as biomass energy, that can provide energy on demand. Nevertheless, there have been several studies considering this combination, as shown in Table 9. Geothermal systems tend to emphasize the use of steam to generate electricity, often with more than one stage.

Table 9. Studies Considering Integration of Geothermal and Biomass Energy

Focus of the Article	Citation
Geothermal with biomass gasification and compressed air storage	Zhang <i>et al.</i> 2019b
Geothermal with biomass digester & hydrogen liquefaction	Meng <i>et al.</i> 2022
Geothermal with biomass gasification with waste heat recovery	Lv <i>et al.</i> 2023
Geothermal with biomass and fuel cells with hydrogen generation	Luo & Taghavi 2024
Geothermal with solar assistance & biomass with steam turbine	Pashapour 2024

Enhanced Biomass Energy Using Solar

Enhanced gasification

Finally, studies with synergistic combinations of solar energy with biomass and other features are considered. The goal here is to improve the hydrogen-generating ability or efficiency of gasification. Table 10 lists studies in which solar energy was utilized for the purpose of enhancing hydrogen production during the gasification of biomass.

Table 10. Studies Considering Integration of Solar and Biomass Energy in Ways that Enhance Hydrogen Production

Focus of the Article	Citation
Solar energy for hydrogen production, with thermodynamics	Yuksel & Ozturk 2016
Solar energy used to promote power, heating, and hydrogen	Wu <i>et al.</i> 2019
Solar (PV) with biomass and hydrogen post-firing & electrolyzer	Cen <i>et al.</i> 2021
Solar energy used to induce chemical looping gasification	Mu <i>et al.</i> 2021
Solar energy used to make hydrogen and ammonia from biomass	Tukenmez <i>et al.</i> 2021
Solar energy to enhance hydrogen production from gasification	Buffi <i>et al.</i> 2022
Solar energy with liquid hydrogen generation from biomass	Meng <i>et al.</i> 2022
Solar energy used to promote hydrogen production from biomass	Takeda <i>et al.</i> 2022
Solar energy molten salt for gasification & hydrogen liquefaction	Assareh <i>et al.</i> 2023
Solar energy used to promote hydrogen from biomass (review)	Lanjekar <i>et al.</i> 2023
Solar energy used to preheat biomass for gasification	Li <i>et al.</i> 2023
Solar energy used to convert biomass to products (review)	Naveen <i>et al.</i> 2023
Solar energy used to preheat biomass for gasification	Ghasemi <i>et al.</i> 2024
Solar energy for biomass gasification with chemical looping	Chen <i>et al.</i> 2024
Solar energy to optimize gasification to make H ₂ for transportation	Cutore <i>et al.</i> 2024
Solar energy with biomass gasification with membrane H ₂ product	Laleh <i>et al.</i> 2024
Solar energy with biomass gasification and catalysis	Lesiak 2024
Solar energy with biomass photoelectric catalysis for H ₂ production	Liu <i>et al.</i> 2024
Solar energy used to induce chemical looping gasification	Mu <i>et al.</i> 2024
Solar energy with catalysis for hydrogen and carbon monoxide	Zhang <i>et al.</i> 2024

Mu *et al.* (2021, 2024) and Chen *et al.* (2024) examined the use of solar energy to enhance a chemical looping reaction, in which water is catalytically split in the course of

gasification, giving rise to increased production of hydrogen. The analysis showed that integration of solar energy rendered the biomass gasification more efficient and more complete. The process appears to be favorable for fuel production (more hydrogen) and in order to decrease the amount of biomass needed to make the fuel. Figure 14, which was inspired by a diagram by Chen *et al.* (2024), illustrates the use of cyclic oxidation and reduction that is part of such looping reaction technology.

Note that the three different iron compounds shown in the figure represent different oxidation states of the iron, namely +3 for hematite, +2 for wüstite, and a mixture of +2 and +3 in the case of magnetite. Transformations between these three species, during the process shown in the figure, make possible the needed redox reaction. Specifically, the wüstite form becomes oxidized to magnetite in the course of the water shift reaction, during which hydrogen is produced in its reduced form. Subsequently, the iron compound is first oxidized during the combustion phase of the process, but subsequently the reducing environment provided by freshly added biomass returns it to the wüstite form, which allows for efficient reuse of the catalyst.

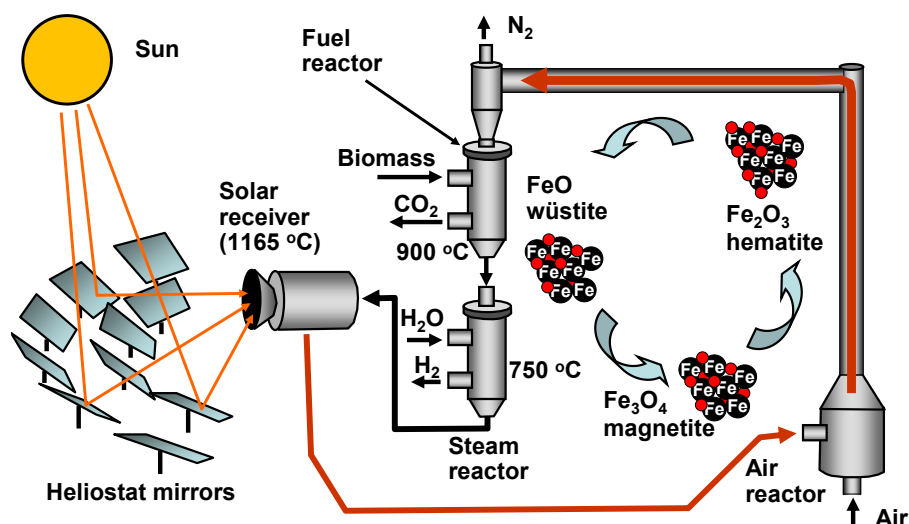


Fig. 14. Schematic diagram of solar-energy-enhanced gasification, using a redox catalyst “looping” system to promote the water shift reaction, thus increasing the proportion of hydrogen present in the resulting syngas

ENVIRONMENTAL IMPACT CONSIDERATIONS

General Issues

While the literature considered in this review article generally indicates favorable environmental effects of the renewable energy technologies studied, especially in comparison with fossil-fuel-based energy production (Buffi *et al.* 2022), it is worth paying attention to details. Environmental considerations of renewable energy must be addressed during the planning and execution of project (Sayed *et al.* 2021; Rahman *et al.* 2022). More than half of the US projects on renewable energy have been stopped or delayed because the environmental impact violated the existing environmental management or standards (Susskind *et al.* 2022).

It is likely that ongoing research can overcome certain problematic aspects that have been identified. For example, although solar energy is generally highly regarded as a way to avoid production of greenhouse gases, the manufacture of solar panels can involve significant environmental impacts, depending on the details and the materials (Muteri *et al.* 2020). Land use change has been identified as an issue in solar energy production, impacting wildlife and promoting habitat loss. Lovich and Ennen (2011) identified the potential effects of utility-scale solar energy development (USSED) during construction and decommissioning as well as operation and maintenance of the facilities, emphasizing topics of wildlife and environmental impacts. Even though wind energy is generally considered favorable with respect to environmental impacts, life cycle assessment (LCA) shows different impacts depending on the location of the facilities and other details (Bonou *et al.* 2016).

Wind energy also raises concerns about wildlife, especially because avian (*i.e.*, birds and bats) collisions with wind turbine towers (Rand and Hoen 2017). However, avian mortality due to wind turbines is somewhat smaller than fossil-based power plants (Sovacool 2013). A recent study has shown that the major emissions of wind power are associated with the manufacture and installation of turbines, such as metal compounds (*i.e.*, aluminum, copper, manganese, molybdenum, among others) extracted during mining (Morozovska *et al.* 2024). Thus, wind energy projects should also be analyzed from mining (and processing of metal compounds for turbine manufacturing) to end-use.

The comparison of life cycle assessment (LCA) studies for bioenergy production is inherently complex due to variations in input data, including feedstock type, system boundaries, functional units, allocation methods, and underlying assumptions. Furthermore, uncertainties and local contextualized factors can introduce discrepancies in the final results. Several researchers have investigated the uncertainty associated with parameters that influence the reliability of LCA outcomes (Wang *et al.* 2020b, Quinn *et al.* 2020). Common approaches for uncertainty assessment include sensitivity analysis and Monte Carlo simulations. For example, Patel and Singh (2024) utilized the LCA methodology to assess the environmental impact of bioethanol production from several agricultural residues, incorporating Monte Carlo simulations to enhance the LCA by accounting for uncertainty and variability in the data. Such analyses necessitate extensive data to ensure the robustness and reliability of the results.

In the discussion that follows, aspects related to LCA will be discussed first for thermal systems, then enzyme-based systems, then for systems emphasizing hydrogen production, and finally for systems that are intended to produce higher-valued fuels or chemical reagents.

Environmental Issues with Thermal Systems

Among the available thermal processes, pyrolysis has been identified as the predominant technology in lignocellulosic biomass LCA analyses (Patel *et al.* 2016). Moreover, feedstock type, technology, system boundaries, and functional units are the critical parameters that influence the final results. Among the different technologies for thermal energy production, several system arrangements could further impact the overall environmental performance. For example, biomass pretreatment (referred to as physical conditioning of biomass through drying and/or comminution) has a greater impact than other unit operations in pyrolysis (Iribarren *et al.* 2012), biomass co-firing decreases the environmental burden more than conventional biomass-fired power plants, but the boiler efficiency is also reduced (Sebastián *et al.* 2011), or using oxygen instead of air may

improve the gasification efficiency but also increase the environmental effects, as the air separation module demands high electricity (Barahmand and Eikeland 2022). By comparing the thermal technologies, combustion has exhibited less environmental impact than gasification, where the Rankine cycle is the most harmful unit due to the emissions released and the energy demanded (Parascanu *et al.* 2019). Moreover, fast pyrolysis has been concluded to be more environmentally friendly than gasification (Alcazar-Ruiz *et al.* 2022).

Another approach for bioenergy production rather than using the feedstock itself is based on biomass pelletization to improve physicochemical properties and efficiencies. Ruiz *et al.* (2018) analyzed the environmental impact of several scenarios based on pellet combustion, finding that combined heat and power (CHP) incorporated into the organic Rankine cycle demonstrates less impact than conventional heat pumps (systems based on natural gas, diesel and electricity). The authors concluded that pellet systems benefit climate change and energy demand but entail more particulate matter formation, water eutrophication, and land use.

Martin-Gamboa *et al.* (2020) considered environmental impacts related to biomass pellet production and usage, using the results of a large number of LCA studies as the main input. The authors noted a wide variation in conclusions when comparing different LCA studies. Such differences can be attributed to variations in methodological choices and their impact on life cycle impacts, in particular global warming and non-renewable primary energy. Most of the articles reviewed had evaluated wood pellets and most of the “cradle to grave” studies had focused on heat generation. However, there are serious differences related to biogenic carbon modeling, the inclusion of greenhouse gases other than carbon dioxide, the method of life cycle impact assessment, impact categories, and the incorporation of sensitivity analysis. For instance, the global warming impact predictions related to pellet technology ranged from -18 to 488 g of CO₂ equivalents per MJ of energy produced from the pellets.

Lee *et al.* (2020) carried out LCA related to the usage of biochar as an energy product. Important environmental impacts of concern were increased eutrophication, acidification, carcinogens, and ecotoxicity impacts. There also was concern that widespread biochar production may lead to a change in land usage, or inappropriate management practices leading to environmental impacts. In general, when studies include analyses of land use change, the impacts tend to be greater.

Hydrothermal carbonization (HTC) has also been investigated as a thermochemical process to produce a carbon-rich fuel product from biomass with high water content, so-called hydrochar (Melo *et al.* 2017). Berge *et al.* (2015) evaluated the LCA associated with energy production from food waste-based hydrochar, noting environmental savings associated with carbon dioxide emissions and acidification potential compared to coal-based energy sources. Likewise, other researchers have concluded that hydrochar produced from green waste (*i.e.*, herbaceous biomass) has the best environmental performance compared to food waste, municipal solid waste, and digestate, where plant size and geographic location for waste management system influence the relative favorability of HTC technologies (Owsianiak *et al.* 2016). Microwave-assisted HTC for electricity generation has also been addressed in the literature, demonstrating that this technology is a more environmentally sustainable approach for fuel production from biomass waste, exhibiting a lower climate change impact than conventional HTCs (Zhang *et al.* 2021).

Environmental Issues with Microbial Systems

Chopra *et al.* (2024) emphasized the importance of pretreatments of biomass, which can have large effects on the overall life-cycle impacts of microbial-based technologies for converting biomass to ethanol and other biofuels. Although much is known about the different pretreatment methods, there are still no comprehensive studies on LCA for different biofuels and different pretreatments that can show a trend towards which pretreatments should be the most successful in order to decrease the environmental impact without decreasing the process yield.

Systems Aimed at Production of Hydrogen

Buffi *et al.* (2022) stated that biomass-based systems involving hydrogen production can have a positive overall effect for the lowering of greenhouse gas emissions, especially if the technology becomes well integrated into the world economy. However, hydrogen production presents multiple processing alternatives, and therefore it is important to note that each has environmental advantages and disadvantages. For example, electrolytic production has serious environmental advantages because of its zero emissions, but the production of the electrolyzers can encourage the use of carbon-intensive materials and the production of the membrane can contribute to photochemical ozone formation (Hoang *et al.* 2020; Schropp *et al.* 2024). On the other hand, hydrogen production by thermal processes such as gasification faces challenges in terms of CO₂ and CO capture after combustion. Garcia-Vallejo *et al.* (2024) performed an analysis on hydrogen production for different production routes. In a cradle-to-gate analysis the carbon footprints of the hydrogen production technologies were 1.34, 4.79, 0.90, and 5.2 kg CO₂ eq/kg of hydrogen in the steam biomethane reforming, gasification, electrolysis, and dark fermentation, respectively.

Higher Value Fuels

Many LCA studies on biofuel have examined the environmental impacts of identical or distinct technologies utilizing a range of feedstocks and/or geographical locations. These studies typically compare various methodological frameworks and data collection practices to assess the variability in the outcomes. However, most biofuel LCAs emphasize carbon footprints, prioritizing climate impacts, often neglecting other environmental impact categories, water footprints, and material flow analyses (Lazarevic and Martin 2016). Indeed, Ridley *et al.* (2012) point out that after reviewing more than 1600 peer-reviewed articles on biofuels, the most frequently discussed topics were production technologies, GHG emissions, and agricultural production of feedstocks. In contrast, the effects of biofuels on biodiversity and human health were far less explored. Though the utilization of biofuels may reduce GHG emissions, it may also lead to an increase in other adverse environmental impacts, such as acidification, human toxicity, and land use changes. These factors should, therefore, be considered in LCAs. For example, Czyrnek-Deletre *et al.* (2017) remark on the need to use different impact categories for biofuel LCAs since it highly depends on the country- or site-specific characterization factors. Osman *et al.* (2024) conducted a comprehensive review of LCAs focused on bioethanol, biodiesel and biogas production as potential biofuels and analyzed the importance of considering environmental sustainability indicators beyond GHG emissions and energy balance.

Although climate change mitigation can be confirmed from biofuels against fossil counterparts, the data on the carbon footprints of biofuels vary between published works.

Gheewala (2023) concluded that the definition of system boundaries and functional unit, as well as the allocation methods and carbon accounting and storage, are the main challenges revealed by LCAs based on biofuels and biochemicals. Bouter *et al.* (2024) also include parameters such as the presence of by-products, type and geographical location of biomass, and the use of land-use change as predominant in the LCA results. Due to the varieties of biofuels, which can be grouped according to their relevance on the market (*i.e.*, bioethanol, biodiesel biomethane, synthetic liquid fuels, hydrotreated vegetable oil, among others), different technologies and feedstocks can be implemented for LCA purposes. Puricelli *et al.* (2021), identified those biofuels with lower climate change than diesel and gasoline in Europe, highlighting savings of 70% for biohydrogen, 63% for biogas, 41% for biodiesel, and 7 to 54% for bioethanol. Patel and Singh (2023) covered a broad range of biofuels from different feedstocks and stated that second-generation biofuels potentially reduce GHG emissions (-15.4 to 178.7 g CO₂ eq. / MJ for bioethanol and -0.21 to 113.8 g CO₂ eq. / MJ for biodiesel) more than conventional fossil-based production and first-generation biofuels (0.006 to 167 g CO₂ eq. / MJ for bioethanol and -7.3 to 329 g CO₂ eq. / MJ for biodiesel). Moreover, third-generation biofuels may increase the GHG emissions (ranging from 10.2 to 1910 g CO₂ eq. / MJ) relative to conventional fuels. Regarding other impact categories, first and second biofuels reduce the energy ratio (ratio between biofuel energy to total energy intake) compared to conventional processes but imply significant water consumption (especially in first-generation) and land-use change.

Inherent Concern about Carbon Emissions, Biogenic or Not

According to the Kyoto Protocol for biogenic carbon neutrality, the carbon dioxide emitted during bioproduct combustions is offset by carbon dioxide sequestration during biomass growth (United Nations 1998). Therefore, an advantage of biofuel combustion over fossil fuels is evident in a reduced projected effect on climate change.

A larger issue, which is unlikely to be easily resolved, is the fact that even though biomass is renewable, its combustion results in the release of carbon dioxide to the atmosphere. Such releases, as in the case of a biomass boiler, can be a major contributor to carbon dioxide emissions (Zhu *et al.* 2024). Assuming unchanged net rates of photosynthesis in the world and no net transfer of the gas to the ocean, *etc.*, then the combined effect will be an increase in greenhouse gas levels. For this reason, there remains uncertainty regarding whether elevated levels of carbon dioxide in the atmosphere can be translated into increased production of biomass (Kramer 1981). In the short term, a positive relationship between carbon dioxide concentration and plant growth is often found, but such a relationship can be expected only up to a threshold level (Bhattacharyya *et al.* 2022). Notably, a positive relationship between carbon dioxide concentration and growth rate of pine trees has been shown (Springer *et al.* 2005). There can be compensatory factors such as the collapse of some plant functions with increasing exposure to higher temperatures. Thus, it would not be safe to predict that the climate change accompanying higher carbon dioxide levels would favorably affect the amounts of living biomass on the planet in future years.

Uncertainties, such as those mentioned above, have implications concerning recommended future policies. For instance, concerns related to whether or not biogenic carbon can be regarded as eco-friendly can be avoided by increased reliance on other renewable energy sources, such as solar and wind. These sources generally do not raise concerns regarding carbon emissions. But by themselves they may be deficient in terms

of their intermittent nature. In addition, solar and wind technologies, by themselves, cannot help usher in a hydrogen-based economy. By their use in combination with biomass, there is such a possibility.

The natural environment has a known ability to accommodate a certain amount of combustion of biomass; thus, it seems reasonable to include biomass among the energy resources upon which we depend. At the same time, priority needs to be placed on sustaining natural resources, including a healthy tree cover throughout traditionally forested lands. Not only do such resources sequester carbon in the biosphere, but they also contribute to the conversion of atmospheric carbon dioxide to oxygen.

TECHNOECONOMIC ANALYSIS

Technoeconomic Analysis of Thermal Processes

Figure 15 summarizes the ranges of cost that have been calculated for the production of a unit of electrical energy by means of many different renewable technologies (IRENA 2012; Baruya 2015). Based on the minimum values shown in the analysis, one can conclude that hydroelectric power can be regarded as having the greatest potential cost-effectiveness, especially if the water impoundment infrastructure is already in place. That is why the estimate labeled “hydro-upgrade” is the lowest of all the options shown. Onshore wind shows relatively low costs. When considering the calculated costs of photovoltaic systems (shown as PT in the figure), it is important to bear in mind the continuing developments in that area of technology, leading to an expectation of ongoing cost reductions. Based on the reported results, it can be established that biomass-to-energy technology costs share the same ranges with onshore wind energy and hydroelectric energy, thus showing comparable cost-effectiveness.

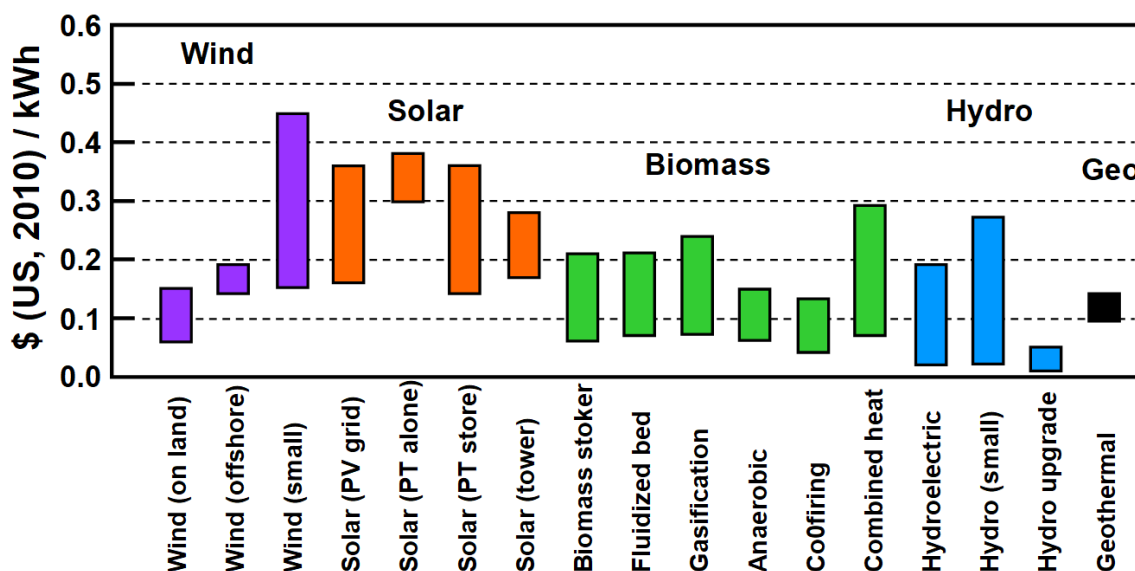


Fig. 15. Calculated costs of producing a unit of electrical energy (US \$/kWh) based on a variety of different renewable paths. The graph has been redrawn from an original provided by the IRENA (2012).

According to Hakeem *et al.* (2023), bioethanol (from enzymatic processing) and syngas (from gasification) can be regarded as the two most cost-effective products derived from biomass-to-energy systems. They described subsequent conversions of bioethanol and syngas to other products, including biobutanol and hydrogen, as being limited by low conversion efficiencies, difficult separations, and challenges associated with biorefining. Likewise, Tezer *et al.* (2022) rated gasification as promising based on their technoeconomic analysis. Sher *et al.* (2024) rated biomass gasification, with the usage of catalytic cracking methods, as achieving a high Technology Readiness Level of 8 to 9. The greatest challenges to that kind of technology were listed as tar formation and challenges in converting the initial products into preferred fuels and chemicals. Hakeem *et al.* (2023) undertook a technoeconomic analysis of various biomass-to-energy systems and concluded that production of ethanol by enzymatic saccharification and fermentation can be counted as a promising technology.

Finally, for hydrogen production, many authors have reported that the most economically viable technology is the production of biomethane by anaerobic digestion with subsequent steam reforming to obtain hydrogen and CO₂ as value-added streams, with a minimum selling price of 1.18 USD/kg H₂. This is followed by biomass gasification with values in the range of (3.0 to 4.82 USD/g H₂). Electrolytic processes and dark fermentation are in the last positions, with values ranging between 6.77 and 10 USD/kg H₂. This is due to the fact that these technologies have low yields and high operating and capital costs respectively (Garcia-Vallejo and Cardona Alzate 2024; Ji and Wang 2021). However, recent review articles indicate technological progress and expected decreases in the cost of electrolysis processes for generation of hydrogen (Koj *et al.* 2024; Pan *et al.* 2025; Ryabicheva *et al.* 2025). For instance, improved economics can be achieved by combining the electrolytic reduction to produce hydrogen with electrolytic oxidation to produce various higher-value compounds in their desirable oxidized states (Vadivel and Murthy 2024).

CONCLUSIONS

1. Based on the literature reviewed in this work, there are a wide range of contributing factors which, added together, can contribute to successful usage of biomass as a renewable energy source. Some favored practices, which involve the selection of the starting material, include the following:
 - Usage of **agricultural residues**, for which the type and location are predictable, which do not compete with food, and which are generally photosynthetically renewable on an annual basis.
 - Usage of **forestry residues**, such as branches, which presently are often left in the forest in disorganized brush-piles. Such material, possibly after onsite densification, could be used to supplement biomass for energy applications.
 - Taking advantage of commonly used practices at pulp and paper facilities, where bark is removed from the tree trunks in a centralized location, thereby making it available for a **hog fuel boiler** system, which can provide steam and electricity.
 - Usage of purpose-grown “**energy crops**,” which might be selected based on their beneficial effects on soil, their ability to grow in places not well suited for food crops, which have high growth rates, and which have low needs for fertilizers or irrigation.

2. When deciding to utilize biomass for purposes of energy production, priority can be placed on situations in which biomass is well suited, such as the following:
 - The need for “**on-demand**” energy input during times when inherently intermittent renewable energy sources, such as solar and wind, are not adequate to meet usage levels.
 - Situations, such as home heating, where the **heat generated as a product of combustion** of the biomass meets an existing need.
 - Systems in which there are opportunities to produce **liquid fuel components**, such as ethanol, butanol, or compounds that could be used in transportation fuels, including aviation fuels.
 - Systems in which **hydrogen can be formed**, especially if this can be accomplished with relatively low environmental impacts.
3. Developers can select from a portfolio of different approaches to converting raw biomass to higher-value energy products, depending on their needs. Some of the most promising include the following:
 - Compression of the biomass to more storable, transportable, and feedable **pellets or briquettes**, which can be conveniently used in boilers, allowing for generation of steam and electricity.
 - Heating of the biomass (either before or after optional compression) to degrade the hemicellulose and render the material less hydroscopic, *i.e.*, **torrefaction**, and thereby increasing its storage stability and effective energy value.
 - Make profitable usage of advances in technology for the construction and operation of **large-scale CFB biomass boiler systems**, which can achieve better fuel flexibility for the generation of steam and electricity.
 - Optimize **mid-range pyrolysis conditions** (350 to 700 °C) conditions in cases where the goal is to prepare a variety of liquid chemical products, which then can be fractionated and modified. This is one known route to prepare high energy density fuel products.
 - Employ **high temperature pyrolysis conditions** (600 to 1300 °C) when the goal is to completely gasify to biomass for the production and usage of syngas.
 - Intensify green hydrogen production through **sorption-enhanced steam reforming and gasification** of biomass feedstocks.
 - Optionally use products of gasification in a **Fischer-Tropsch process** to prepare a variety of organic compounds, especially aliphatic liquid products.
 - Achieve a range of liquid compounds such as levulinic acid and furfural-related compounds from biomass at much lower temperatures by **hydrothermal liquefaction**.
 - Instead of using thermal technologies, instead carry out **acid-catalyzed hydrolysis or enzymatic hydrolysis of biomass**, followed by or in combination with fermentation to produce ethanol, butanol, or other products that can be obtained by further reactions.
4. Synergistic advantages can be obtained by means of advantageous combinations of biomass-derived energy and other types of renewable energy.
 - **Micro-grid and medium-sized grid systems** can be set up in which software controls the integration of biomass energy in combination with either wind

energy or solar energy in a way that provides reliable power in the quantities needed by the people served.

- By careful design of a ***biomass gasification system in combination with reflective collection and concentration of solar heat***, emerging technology may be able to produce hydrogen more efficiently. In this way, biomass resources can contribute to a future hydrogen economy. Benefits can include lower greenhouse gas impacts and lower pollution.
 - Because it is important to slow down the rate of emissions of CO₂ to the atmosphere, regardless of the source, it is important to prioritize the development and implementation of solar, wind, hydroelectric, and geothermal energy technologies.
5. The transition to renewable energy systems presents a critical opportunity to reduce greenhouse gas emissions and advance sustainability goals. However, the environmental impact associated with the life cycles of these technologies must be evaluated carefully.
- LCA has emerged as a vital tool in identifying environmental impacts. However, several methodological approaches continue to challenge the comparability and reliability of results. A multidimensional and context-sensitive approach to environmental evaluation is encouraged.
 - Solar and wind energy, while often regarded as environmentally friendly, can result in significant ecological disruptions, particularly related to manufacturing processes. Thermal and bioenergy (from biofuels) technologies exhibit complex environmental trade-offs influenced by system configurations, technological pathways, and site-specific conditions.
 - Effective energy planning and policymaking must incorporate comprehensive LCAs considering climate change mitigation and impacts on land use, water resources, human health, and ecosystems.
 - Future research should focus on improving data quality and expanding the scope of environmental indicators to ensure that renewable energy solutions are truly sustainable across their full life cycle.
6. There will be a continuing need for technoeconomic assessment studies in this area. Work considered in this review supports the following conclusions:
- The environmental impacts of energy carriers such as hydrogen and jet fuel will depend significantly on the selected pathway and feedstock. In addition, the effective distribution and market expansion of these energy carriers will be linked to the political disposition to provide economic or environmental credits that will allow these carriers to be economically competitive.
 - Expansion in the use of sustainable jet fuels will depend on the ability of researchers to develop and optimize processes to achieve higher energy density and performance, which will allow viable operating costs in the commercial sector.

ACKNOWLEDGMENTS

The authors wish to thank the following people who studied an earlier version of this article and offered their corrections and suggestions: Xun Guan, School of Engineering, Huzhou University, P. R. China; and Liang Zhao, College of Materials Science and Engineering, Nanjing Forestry University, P. R. China. The work of Martin Hubbe is supported by an endowment from the Buckman Foundation.

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