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Biomass as a renewable energy source for water desalination: a review

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ABSTRACT

Water desalination is an energy-intensive process needed in many parts of the world to provide fresh water for drinking, agriculture, and industry. The energy for desalination can come from conventional fossil fuels such as petroleum, natural gas, and coal, as well as renewable energy sources such as solar, wind, hydro, and geothermal. One renewable energy source that is widely available but currently unused for water desalination is biomass. The goal of this review was to understand why this is, how biomass compares to other renewable energy sources for water desalination, and under what circumstances the moveable and non-intermittent nature of biomass may provide advantages. The main limitation for biomass is cost, driven by the needed feedstock volumes and process complexity. Biomass-to-heat for thermal desalination technologies is simpler but more energy-intensive. Biomass-to-electricity for membrane desalination uses less energy but has complex processes. Biomass use will likely remain limited to small-scale capacity needs, infrastructure-poor or rural areas with few other options, brackish waters, and abundant, underutilized biomass supplies.

Keywords: Water desalination; Multiple effect distillation; Renewable energy; Biomass

1. Introduction

The need for high-quality water is dramatically increasing due to rapid population growth, higher per capita water consumption, greater industrial and power generation water use, and expanding agricultural production. As such, there is an ever-increasing need for techniques to purify water to overcome freshwater shortages. Water desalination is a standard technique for providing large quantities of high quality, potable water worldwide [1]. The total desalination capacity throughout the world was 38 million m^3/d in 2004 [2], 75 million m^3/d in 2012 [3], 81 million m^3/d in 2013, and more than 100 million m^3/d in 2015 [4]. Concerns about petroleum-based energy availability and environmental impacts have motivated the exploration of alternative and renewable energy sources for water desalination [5,6].

Although the produced water costs of renewable desalination technologies are still more expensive than fossil fuel-driven technologies, they are likely a suitable option for remote areas that lack connection to electrical grid infrastructure and that have access to renewable energy sources [7–9]. Various combinations of desalination and renewable energy have been studied [4,10]. The most common renewable energy sources for water desalination are solar photovoltaic (PV), solar thermal, wind, and geothermal, and hybrids of these options [4]. In 2018, there were 131 renewable-energy driven desalination plants (about 1% of global desalination capacity); 43% of these were powered by solar PV, 27% by solar thermal, 20% by wind, and 10% by hybrid renewable energy sources [6]. Many researchers have suggested that novel desalination methods, such as membrane distillation (MD) or adsorption desalination (AD), combined with hybrids of renewable energy sources, may reduce energy consumption and produced water cost [9]. Currently, solar-MD is at the R&D stage with high energy consumption and high production costs of 10.4–19.5 USD/m^3, compared

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to 2.6–6.5 USD/m^3 for solar-multiple effect distillation (MED) or 3.9–6.5 USD/m^3 for wind-reverse osmosis (RO) [6].

Even though there have been many improvements in solar and wind energy-powered desalination, both energy sources are weather dependent and intermittent [6]. Several existing solar desalination plants have failed due to these technological limitations, or have had to be connected to the grid due to the intermittency of solar energy. Thermal energy storage can be used to address the intermittency but results in further complications and higher costs [11]. Geothermal energy is not intermittent and provides continuous low-grade heat; however, the capital costs, design complications, and environmental impacts have limited its application for water desalination [12].

Biomass energy does not have the same limitations as solar or wind energy, yet few literature studies mention it. Belessiotis et al. [13] recommended biomass energy as an alternative to power water desalination in remote areas. Eltawil et al. [10] argued against using organic residues for water desalination due to their limited availability in arid regions and the high needs of freshwater to grow biomass. Strict regulations on field burning of agricultural residues, the presence of concentrated point sources of biomass at processing facilities, and the high costs of transporting biomass over distances may create an opportunity to use local biomass energy in certain arid and semiarid agricultural/forest locations, such as in California [14].

In this literature review, we compare renewable energy-driven desalination technologies and the challenges they face. We then explore the potential use of biomass as an energy source for water desalination to see if options exist that warrant further research.

2. Water chemistry and desalination

Water quality is categorized as a function of total dissolved solids (TDS) in parts per million (mg/L): freshwater contains 200–700 ppm, treated wastewater contains 700–1,500 ppm, brackish water contains 2,000–10,000 ppm, and seawater contains 30,000–60,000 ppm. Approximately 58% and 23% of the installed water desalination capacity worldwide are used for treating seawater and brackish water, respectively [10]. One significant difference between brackish water and seawater desalination is the method of brine disposal. For seawater desalination plants, the brine is discharged back into the ocean; significant additional expenses are associated with brine disposal for inland desalination plants as discharge is not possible [15]. Another difference between seawater and brackish water desalination is water chemistry. The TDS of seawater is significantly higher and consists primarily of sodium and chloride, which are not problematic in desalination systems [16,17]. Brackish water, on the other hand, frequently contains bicarbonate, sulfate, and calcium, which can cause scaling. Table 1 compares the SO_4^{2-} and HCO_3^- of different brackish and seawater samples worldwide. Even though the TDS of brackish water is substantially lower than that of the seawater, the SO_4^{2-} and HCO_3^- content can be higher. These two anions react with Ca^{2+} to form $CaSO_4$ and $CaCO_3$, which are only sparingly soluble and whose solubility decreases with increasing temperature.

3. Desalination technologies

Depending on the TDS of the water, treatment costs, and infrastructure availability, a variety of desalination techniques can be used. These techniques are grouped into membrane/single-phase processes, such as RO, and thermal/phase-change processes, such as multi-stage flash (MSF) and MED [1,5,24,25]. AD and MD are two desalination technologies that are much less energy- and chemical-intensive compared to traditional methods, and therefore are candidates to couple with intermittent renewable energy sources, such as solar energy [4].

3.1. Membrane processes

The two primary membrane desalination processes are electrodialysis (ED) and RO. Both require electrical energy to drive the separation process. In ED, anion-permeable and cation-permeable membranes, in combination with a cathode and an anode, draw salt ions outward from dilute feed steams into concentrated brine streams. In RO, which accounts for more than 88% of the membrane process capacity worldwide, hydraulic pressure overcomes osmotic pressure to force water molecules through a semi-permeable

Table 1
Comparison of total dissolved solids (TDS), sulfate (SO_4), and bicarbonate (HCO_3) concentrations in various sources of saline water

	HCO_3 (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Reference
Seine River, France	106	53	408	[18]
Nur Spring, Israel	0	931	3,590	[19]
Brackish Water, Saudi Arabia	241	611	3,329	[20]
Brackish Water, Iran	903	1,080	2,930	[21]
Brackish Water, California, U.S.	291	1,020	5,250	[22]
Brackish Water, New Mexico, U.S.[a]	301	2,810	5,390	
Brackish Water, Tunisia	51	2,431	5,261	[23]
Standard Seawater	107	2,412	35,000	[16]
Persian Gulf	160	3,000	45,000	[17]

[a]U.S. Bureau of Reclamation 2017 well water data for Brackish Groundwater National Desalination Research Facility (available https://www.usbr.gov/research/bgndrf/water.html).

membrane (pore sizes < 10 Å) from a stream with low ion concentration to a stream with high ion concentration. RO is usually more cost-effective for water with TDS values less than 5,000 ppm, while ED is more economical for water with TDS values higher than 5,000 ppm [10,26].

Water pre-treatments such as nanofiltration, ultrafiltration, sterilization, and the addition of chemicals, are usually needed to prevent scaling and bio-fouling in RO and ED [26,27]. More detailed information on membrane desalination process design and membrane scaling can be obtained in [27,28].

3.2. Thermal processes

There are three main types of thermal desalination processes: MSF, vapor compression distillation, and MED. All three require low-temperature heat as the primary energy input and a small amount of electricity to drive fluid and vacuum pumps. Some advantages of thermal desalination over membrane desalination processes are higher quality product water, no membrane replacement costs, lower sensitivity to changes in feed water quality, and less rigid monitoring requirements [10,29,30].

3.3. Adsorption desalination

AD is a low-maintenance desalination system that utilizes a low-temperature heat source to power sorption cycles. AD is used for both freshwater production and cooling. An adsorbent, such as silica gel with a pore diameter of 10–40 nm, adsorbs the vapor produced in the evaporator at low temperature and pressure. The adsorbed vapor is then released by heating the adsorbent. AD systems can handle very high salinity (up to 250,000 ppm) with minimum scaling due to the low evaporation temperatures. Since AD involves evaporation, the produced freshwater has a TDS of less than 10 ppm with a recovery of 70%, even from high-salinity feedwater [31]. The heat transfer medium for AD is hot water (55°C–85°C), which can be easily provided by geothermal or solar energy [4]. More information on AD can be found in [32–34].

3.4. Membrane distillation

MD is a desalination process whose driving force is the partial vapor pressure across the hydrophobic microporous membrane with a temperature difference of 7°C–10°C. When heated feedwater contacts the membrane, the produced vapor transfers to the cold permeate side, where it is condensed and collected. MD operates at atmospheric pressure and temperatures of 50°C–90°C, with no metallic construction materials. These features reduce concerns for corrosion and scaling and make MD a promising candidate for small-scale applications using low-grade waste heat such as solar energy, geothermal, and biomass [4,35–38]. Detailed reviews on MD systems can be found in [36,39–41].

4. Energy requirements for desalination

As a generalization, water desalination plants use about 4–20 kWh/m^3 (14–72 MJ/m^3) of electrical energy equivalent to produce freshwater. If thermal energy had to be converted to produce electrical energy (at ~30% efficiency), this value would be approximately 46–240 MJ/m^3 [26]. Desalination energy consumption contributes about 60% of the water production costs [26]. For an optimized desalination system, the energy costs can be decreased to 30%–44% of total water production costs [42].

The amount of energy needed for water desalination is dependent on many factors, such as the form of energy (electrical or thermal), the plant capacity, the plant design configuration, and the feedwater chemistry. The energy needed for MED and MSF processes is much higher than that required for RO because of the water evaporation step in thermal processes, and significant improvements in RO technology that have lowered its power consumption [5,43].

A summary of water desalination plant capacities, energy requirements, and produced water costs for small-scale plants is shown in Table 2. Due to economies of scale, the energy and cost requirements for small-scale plants are much higher than those for more typical, large-scale plants. If electrical energy is needed for the process, the values in the table assume that thermal energy is converted to electrical energy with a 30% efficiency. For example, if 1 kWh/m^3 (3.6 MJ/m^3) of electrical energy was needed for water desalination—as described in the original reference, the table shows 12 MJ/m^3, indicating that 12 MJ/m^3 of thermal energy was needed to produce the desired amount of electrical energy.

4.1. Energy consumption in RO

A typical RO unit with an energy recovery system and a plant capacity of up to 128,000 m^3/d for seawater and 98,000 m^3/d for brackish water, consumes 14.4–21.6 MJ/m^3 (4–6 kWh/m^3) and 5.4–9 MJ/m^3 (1.5–2.5 kWh/m^3) of electrical energy, respectively. This difference in energy requirements is the primary cost difference between treating seawater and brackish water with RO. High TDS concentrations result in more energy consumption in RO at a rate of approximately 3.6 MJ/m^3 (1 kWh/m^3) per 10,000 ppm [24].

4.2. Energy consumption in MSF and MED

The factors that affect energy consumption in MSF systems are temperature of the heat sink, number and geometry of the stages, feedwater TDS, unit construction materials, and heat exchanger configuration. Increasing the gain output ratio (GOR), the number of stages and the heat transfer surface area are all ways to lower energy consumption [26,28,42,46]. From design information provided by commercial manufacturers, a typical MSF, with a production rate of 50,000–70,000 m^3/d and a GOR of 8 to 12, consumes between 190 and 282 MJ/m^3 of thermal energy, and 13.5 MJ/m^3 (3.75 kWh/m^3) of electrical energy to drive the pumps [26,42].

Similar to MSF, MED needs thermal energy for water evaporation and electrical energy to drive pumps. A typical MED unit with a production rate of 5,000–15,000 m^3/d, operating at a top brine temperature of 64°C–70°C, and a GOR of 10 to 16, requires 145 to 230 MJ/m^3 of thermal energy and 8.1 MJ/m^3 (2.25 kWh/m^3) of electrical energy [26,42].

Table 2
Water desalination plant capacities, thermal energy requirements (assuming a 30% efficiency for conversion of thermal energy to electrical energy if required), and water production costs for some small-scale (<100 m^3/d) conventional and renewable energy-powered desalination technologies

Method	Size (m^3/d)	Water	Energy (MJ/m^3) Electrical	Thermal	Cost (US$/m^3)	Reference
Conventional MED (single-purpose)	<100	Seawater	–	–	2.0–8.0	[26]
Diesel MED	4	Brackish	–	1,110	26.50	[44]
Conventional RO	20–1,200	Brackish	–	–	0.78–1.33	[45]
Solar still	<100	–	0	Passive solar	1.3–6.5	[26]
Solar multiple effect humidification	1–100	–	18	355	2.6–6.5	[26]
Solar MED	1	Brackish	–	–	25.3	[8]
Solar MED	72	Seawater	–	–	3.6–4.35	[8]
Solar membrane distillation	0.15–10	–	0	540–708	10.5–19.5	[26]
Solar PV RO	<100	Seawater	48–72	0	11.7–15.36	[26]
Solar PV RO	<100	Brackish	18–48	0	6.5–9.1	[26]
Solar PV ED	<100	–	18–48	0	10.4–11.7	[26]
Wind RO	19	Seawater	–	–	4.4–7.3	[8]
Wind RO	12	Seawater	–	–	2.6	[8]
Wind mechanical vapor compression	<100	–	84–144	0	5.2–7.8	[26]
Geothermal MED	80	–	24–36	149–289	2.0–2.80	[26]

Energy consumption and hence, the final produced water cost, is significantly reduced in thermal desalination units if the power source is dual-purpose, that is, the low-temperature exhaust heat energy (usually wasted in cooling towers, solar ponds, and solid waste incinerators) provides the primary steam for desalination [47]. This is how most of the thermal desalination plants are powered in the Middle East. For instance, the produced water cost of a 6 million gallon per day (22,700 m^3/d) single-purpose MED unit would be 0.739 cents/gallon (1.95 US$/m^3), while the produced water cost from a similar capacity dual-purpose unit would decrease to 0.330 cents/gallon (0.87 US$/m^3) [10,26,42].

4.3. Energy consumption in AD

AD is much less energy-intensive compared to MED and MSF. As the waste heat or renewable energy sources are typically used, the specific electrical energy consumption in AD, for the three water pumps and pneumatic valves, is about 1.38 kWh/m^3. For a hybrid of MED and AD, the specific energy consumption increases to 1.94 kWh/m^3. In comparison, the typical specific energy consumption (electrical) of MED, MSF, and RO is 2, 2.5, and 5 kWh/m^3, respectively [4,31].

4.4. Energy consumption in MD

MD requires electrical energy for water circulation and thermal energy for phase conversion. Assuming thermal energy from a waste heat source, the specific energy consumption to drive the pumps in MD can be as low as 1 kWh/m^3 [4]. Duong et al. [38] found that an air gap MD system consumes 90 kWh/m^3 of thermal energy and 0.13 kWh/m^3 of electrical energy, making it appropriate for small-scale, solar-powered seawater desalination.

5. Energy sources for desalination

5.1. Fossil fuel energy

Fossil fuels, such as coal, crude oil, and natural gas, are the most common fuels for power production worldwide. Conventional water desalination technologies, especially those with the highest capacities in the Middle East, are powered by fossil fuels. Concerns about future availability, greenhouse gas emissions, and environmental impacts of fossil fuels have helped drive the focus for future water desalination technologies (and power generation in general) towards energy efficiency and harnessing renewable energy sources [48].

Nisan et al. showed that, at present, coal prices, the integration of RO or MED water desalination systems with circulating-fluidized-bed coal-fired power plants would result in the lowest power and desalination costs, while oil-fired power production would result in the highest desalination costs. From an environmental impact analysis perspective, RO with a combined cycle gas turbine power plant has the lowest emissions of NO_x, SO_x, CO_2, and particulates, while MSF with a coal-fired power plant has the highest emissions [48]. Methnani [49] showed that RO water desalination, coupled with any fossil fuel, would have lower costs than MED due to the lower energy requirements for RO. This difference in costs, however, is negligible except when treating very high salinity water.

5.2. Renewable energy

Factors to consider when pairing renewable energy and desalination technologies include type, amount, and cost of available energy, site topography, and geographical conditions, plant size, feed water salinity, local infrastructure, and water distribution costs. Currently, only 1% of the desalination plants worldwide are powered by a renewable energy source. The limited use of renewable energy for desalination could be partially due to the lack of information/education/training, high capital costs, and the need for complex energy storage systems due to the stochastic nature of renewable energy [11]. When thermal energy is available, coupling renewable energy with a distillation process, such as MSF and MED, may be a good option. MED systems are preferred to MSF due to their lower scaling and energy consumption, and their greater flexibility for different capacities. 13% of renewable energy-desalination systems are solar-MED, and 6% are solar-MSF. Possible combinations of renewable energy sources and water desalination methods are available in [9–11].

5.2.1. Solar-water desalination

Several configurations use solar power water desalination; the configurations are divided into two main categories: direct and indirect collection systems. Solar-PV is the most promising [4,50,51]. Indirect technologies are suitable for medium to large-scale desalination systems; direct methods employing solar stills are preferred for small-scale applications [52]. Solar energy is used to produce electrical energy by converting it directly into electricity, as is done in PV, or converting solar thermal energy into electricity through a steam turbine at a 40% energy loss. For this reason, solar-desalination technologies mostly rely on pressure and thermal energy to operate rather than electricity. For remote arid areas, further research and development are required for solar desalination due to the substantial deployment risks, such as lower-than-expected efficiencies and higher-than-expected costs in previous deployments [51]. Other factors that might limit the application of solar desalination are weather conditions and the availability of suitable energy storage technology [53].

5.2.2. Hydroelectric energy and water desalination

Hydropower is generated using the gravitational potential energy stored in water by damming rivers. Low-temperature waste heat from a hydropower turbine can be used as the thermal energy source for MSF and MED. Hydro-MSF is the most effective combination in terms of reducing airborne emissions (79% decrease) compared to fossil fuel-MSF; the results were similar (71% airborne emissions decrease) for hydro-MED [1,54,55]. The limitations of hydropower desalination are that it is capital-intensive and restricted to locations with suitable rivers [1].

5.2.3. Wind energy and water desalination

Wind, the result of atmospheric pressure differences caused by solar energy, can be used for powering desalination units, especially in remote areas with high potential wind speed, such as islands [5,56]. Because of weather-related wind speed fluctuations, efficient backup power systems such as diesel generators, batteries, or flywheels are needed to stabilize the energy production rates [7,57]. One significant advantage of wind energy is its low cost compared to other renewable technologies since it is locally available and does not require much water transportation from treatment location to the end-user. Wind turbines can be coupled with several desalination technologies, though they have mostly been used with RO systems. The amount of treated water that can be produced efficiently by a wind-RO system is 50 to 2,000 m^3/d [10,26]. More information on wind-powered desalination is available in [8,56,58–64].

5.2.4. Geothermal energy and water desalination

Geothermal energy is the heat energy stored beneath the earth's surface. Geothermal reservoirs can be low temperature (<150°C) or high temperature (>150°C); water temperature directly affects the available application for geothermal energy. High-temperature geothermal reservoirs (from underground depths of 1,000–3,000 m) are suitable for electricity-driven desalination technologies such as RO. Even though they are closer to the surface and more accessible, low-temperature reservoirs have attracted little attention for water desalination purposes due to the poor economic feasibility of such systems. Despite high exploration and installation costs, and the investment risks of high-temperature geothermal desalination systems, the consistent availability of free geothermal energy and the lack of need for energy storage (as opposed to solar or wind energy) offset the high costs [4,65]. As described in a report by Awerbuch [66], the first geothermal-desalination pilot plant was built in Holtville, California, in 1972, funded by the U.S. Bureau of Reclamation [10,26]. Sometimes, the brine from geothermal desalination systems can be used directly as a feedwater/heat source for thermal desalination, or even RO, if the membrane can withstand higher temperatures (60°C–90°C). If a geothermal reservoir can provide water with a high enough pressure, it could provide the shaft energy for mechanically driven desalination processes [67,68]. The use of geothermal desalination has been justified for decentralized, small-scale applications in coastal regions. However, commercial application has been slowed by technical design problems and high investment costs [69].

6. Biomass

6.1. Biomass energy and water desalination

The energy content of dry lignocellulosic biomass typically ranges from 15–20 MJ/kg, compared to approximately 43–47 MJ/kg for crude oil, gasoline and diesel, and 50–54 MJ/kg for natural gas. Non-food biomass, however, is abundant in many places in the form of agricultural residues, forestry residues, yard waste, and construction wood waste [70]. Many of these residues go underutilized in landfills, especially in rural areas where there is less pressure for waste valorization—and less access to fossil fuel and electricity infrastructure. For those areas that require small-scale brackish water desalination, communities should consider biomass-powered water treatment systems; while such systems do not represent global optimization in terms of energy efficiency or cost, they may allow communities to meet their needs with what they already have [71]. For large-scale applications, transportation costs limit the use of biomass energy to centralized biomass/food processing facilities that are already generating bio-waste on-site (in a fashion similar to siting thermal desalination next to cogeneration power plants where the waste heat is used to desalinate water) [72].

6.2. Biomass as an energy source

Biomass is exceptional among renewable energy options in that it can be both a source of energy and a source of materials. In this way, biomass is more like petroleum and coal, but with much faster replenishment times and lower net CO_2 emissions. According to the U.S. Department of Energy's 2011 report, the total annual energy consumption in the U.S. is about 98 billion GJ, for which biomass contributes about 4%. The annual biomass production rate in the U.S. is approximately 214 million dry tons (Mg): 129 million Mg as forest resources and 85 million Mg as agricultural resources [73,74]. By 2022, U.S. is expected to produce 290 Mg of biomass in agricultural sectors as residues and energy crops, and 84 Mg from the forest sector as mill waste and logging residues; these have the potential to provide 20% and 10% of U.S. future electricity consumption, respectively [75]. The main advantages of using waste biomass sources are their relatively low costs and the potential for carbon-neutral or even carbon-negative energy [76]. Compared to petroleum or coal, the disadvantages of using biomass for energy production include: (1) lower bulk densities, (2) lower energy contents, (3) higher moisture content (which can create both transportation and storage problems due to weight and decomposition, respectively), and (4) higher heterogeneity as a material [77]. Biomass can have a significant variation in its availability, composition, and characteristics from one season to another, and one location to another.

Lignocellulosic biomass resources used for energy usually come from one of two categories: wastes or dedicated energy crops. Wastes include yard wastes, municipal solid wastes, agricultural residues, food waste, forestry materials, and animal byproducts. Dedicated energy crops (not the focus of this review) are plants grown explicitly for energy production and include herbaceous energy crops such as switchgrass, short-rotation woody crops, and oleaginous (lipid-rich) crops [74].

The suitability of biomass for energy production is dependent on several of its properties, including composition, energy content, density, and production yield. One method of characterizing biomass composition for energy applications is proximate analysis, which measures moisture, volatile matter, fixed carbon, and ash content by thermogravimetric analysis. Moisture represents the weight that does not contribute to the samples' energy value. Volatile matter is typically defined as the portion of biomass that decomposes and volatilizes under heating in a non-oxidizing environment. Fixed carbon is the fraction of organic matter that does not volatilize under heating; knowledge of both values is essential for designing biomass burners and thermochemical processing unit operations. Ash is composed of inorganic minerals/nutrients contained in the biomass, and, like moisture content, does not contribute to its energy value [73,74].

There are two essential kinds of density for evaluating biomass as an energy source: bulk density (kg/m^3), and energy density or volumetric energy content (GJ/m^3). Both densities are related by higher heating value (HHV) and are critical for biomass handling and transportation logistics; the lower the energy density, the more vehicle space is required to transport a given amount of energy [74]. Table 3 compares the bulk and energy densities of several kinds of fuel. Both bulk and energy density are significantly lower for biomass than for fossil fuels. Densification of the the biomass can increase the bulk density as much as ten-fold, as well as create biomass particles with homogeneous size and shape, and greater durability, which improves biomass fuel handling, transportation, and storage. The most common densification technologies include the pellet mill, screw extruder, and briquette press. The process variables that influence the densification process include biomass moisture content and composition, compression pressure, and particle size [71]. Among all biomass components (cellulose, hemicellulose, lignin, and extractives), cellulose is the only component that has a steady HHV of almost 18 MJ/kg due to the consistency of its chemical structure. For lignin, HHV varies over a range of 23–26 MJ/kg. In general, biomass that contains more lignin has higher energy content than biomass composed of mostly carbohydrates [78].

6.3. Process heat from biomass

Lignocellulosic biomass may be directly burned as a solid fuel or converted to produce flammable gases and liquids. Biomass solid fuel furnace systems have two general configurations: direct-fired and indirect-fired. In direct-fired furnaces, the process stream is in direct contact with the combustion flue gas or the fuel is burned in the process stream; in indirect-fired furnaces, the combustion products are separated from the process stream using a thermally conducting wall or air-to-air heat exchangers. In direct firing, there is a high chance that the process stream is contaminated with the flue gas components, while in indirect firing, there are no such problems [71]. If the biomass solids are to be converted first, there are two broad conversion technology platforms: biological/biochemical and thermochemical/catalytic. The biological/biochemical conversion platform includes hydrolysis, fermentation, anaerobic digestion, and composting technologies. This platform is most often used for waste management and liquid fuels production; these technologies are most appropriate for when the biomass moisture content is high. The thermochemical/catalytic platform includes combustion, gasification, pyrolysis, solvolysis, and torrefaction technologies, which all require the biomass to be dried before undergoing conversion [71]. This review focuses on the thermochemical platform technologies as these technologies are more closely connected to process heat generation.

6.3.1. Combustion

Biomass direct combustion is the oxidation of biomass at moderate to high temperatures to produce heat for drying, space heating, power generation, etc. Most biomass combustors currently in use are for low-pressure steam production for process heat or high-pressure steam production for power generation. Combustion consists of four stages: (1) heating and drying, (2) pyrolysis, (3) flaming pyrolysis,

Table 3
Higher heating value (HHV), density, and energy density of different fuels [79,80]

Fuel	HHV (MJ/kg)	Bulk density (kg/m^3)	Volumetric energy content (GJ/m^3)
Diesel	46	850	39.1
Gasoline	48.2	740	35.7
Coal	18.3–36.7	600–900	11–33
Hardwood	18.9	280–480	5.3–9.1
Softwood	20	200–340	4–6.8
Agricultural residues	16–18	50–200	0.8–3.6
Nut shells	20.3	64	1.3
Animal manure	17.4	400	6.9
Municipal solid waste	19.9	–	–
Orchard prunings	19.1	–	–
Sunflower shells	17.9	64	1.1
Methanol	22.3	790	17.6
Ethanol	29.7	790	23.5
Biomass pyrolysis oil	8.3	1,280	10.6

and (4) char combustion. Excess oxygen is available throughout the whole process, even if oxygen is only needed for the third and fourth stages [81,82].

6.3.2. Gasification

Gasification is combustion at slightly lower temperatures (750°C–1,500°C) with less than the stoichiometric amount of oxygen, resulting in mostly CO and H_2 (synthesis gas or "syngas") rather than CO_2 and water. Syngas is flammable and also contains small amounts of CO_2, CH_4, H_2S, and NH_3. If syngas contains a significant amount of N_2 from using air as the oxidant, it is called producer gas. Syngas/producer gas can be used for thermal energy generation in much the same way as natural gas, or as the feedstock for making liquid fuels and other chemicals. The high volatile matter content of the biomass (70%–90%), compared to many coals (30%–40%), as well as the high reactivity of the biomass char, make biomass a suitable feedstock for gasification [77].

Two challenges when designing biomass gasification and combustion reactors are how to treat incompletely-reacted tars and how to avoid sintering and other reactor component damage from the ash fraction [73]. More information on biomass gasification, syngas cleaning and conditioning, and follow-on reactions can be found in [83–85].

6.3.3. Pyrolysis and torrefaction

Pyrolysis is the heating and decomposition of biomass in the absence (or limitation) of oxygen, representing the first two stages of combustion. Torrefaction is a low-temperature pyrolysis (200°C–300°C) used as a pretreatment to remove water and easily-degradable compounds from biomass to increase its friability and energy density [86]. Pyrolysis is usually conducted at moderate temperatures (400°C–600°C). Biomass pyrolysis products include all three phases: gases (mostly CO, H_2, CO_2, CH_4, and C_2H_2), liquids (bio-oil/tar and water), and solids (biochar/ash). The distribution of products depends on the biomass used and the operating conditions. Fast pyrolysis uses dynamic controls to optimize the yield of liquid products. Non-condensable pyrolysis gases can be the direct products of biomass decomposition, as well as the secondary products from liquid tar cracking and char gasification. Gas production is typically favored by higher temperatures, longer reaction times, and smaller particle sizes [77]. Although pyrolysis gas has a low heating value, its energy content can be higher than that of producer gas from gasification and, therefore, it may still be suitable for thermal energy production [85,86].

Biochar is the carbon-rich solid product of pyrolysis that can be used as a solid fuel, a feedstock for activated carbon adsorbents, and as a soil amendment to improve soil fertility and sequester carbon [87]. Yields of biochar are usually 15%–20% for fast pyrolysis and 20%–50% for slow pyrolysis on a dry biomass weight basis, depending on the pyrolysis temperature. Lignin content in biomass favors char formation [87–89]. For slow pyrolysis in a temperature range of 450°C–500°C, the process produces about 0.26 kg of char per kg of biomass, with approximately 45% of the biomass carbon being retained in the char [90]. The HHV for biochar and coals is similar (13–23 MJ/kg), and slow pyrolysis favors higher char HHV than fast pyrolysis or gasification [91].

7. Small-scale renewable energy-desalination technologies

Currently, small-scale renewable energy-powered water desalination systems are economically feasible only in rural communities with no access to an electrical grid, and/or where solar, geothermal, and wind resources are abundant [4,10,92]. Produced freshwater costs generally increase as plant capacity decreases and as renewable energy sources are used. Although many forms of renewable energy sources are available for free or very low cost, significant upfront capital is needed. Small-scale desalination systems and their economics are very important for small rural communities where the available water is brackish or contaminated, and a decentralized system is needed. Sen et al. designed a small-scale desalination system for rural communities in India [93].

They developed a micro-scale MED system, initially powered by diesel, with a freshwater production rate of 11–12 L/h (0.27 m^3/d) [94]. In another series of studies, Sen et al. experimented with 3, 6 and 9-effect MED systems [44,94,95]. The 9-effect MED at semi-optimized parameters produced 4 m^3/d and required approximately 1,110 MJ/m^3 of thermal energy for the diesel baby boiler at the cost of approximately 26.5 US$/$m^3$ (assuming a diesel energy content of 43 MJ/L, a cost of 0.86 US$/L, and a density of 0.832 kg/L) [44].

Several small-scale desalination systems have been deployed in remote regions, including solar-desalination [57,96–100], wind-powered desalination [101–104], or solar-wind hybrid desalination [105]. Many such systems have failed due to a lack of workforce, technological limitations, and needs for energy storage [11,106,107]. Researchers have suggested coupling solar and wind desalination with a municipal power grid, or a permanent renewable energy source such as geothermal energy, to account for the intermittency of wind and solar energy [4,101].

Biomass energy is best suited for decentralized applications to decrease biomass transportation costs. This means that biomass desalination would have to fit within the already limited scenarios for feasible small-scale systems. For remote areas where the electricity is limited, biomass is abundant, feedwater is saline and contaminated with pathogens, and membrane-adverse elements such as arsenic and boron are present, such as in some African countries where more than 50% of energy consumption comes from biomass [108], biomass-driven MED or MD systems [109,110] may be candidates as they also disinfect the water at relatively high temperatures (more than 50°C). Such systems might be especially suitable for remote medical facilities where water quality is critical. Amiri et al. [76] modeled a small-scale biomass-driven MED system powered by slow pyrolysis that could also work for sterilization purposes in medical settings in remote areas. They identified design and operating parameters to decrease costs. If the produced freshwater is to be used for drinking or irrigation (less stringent TDS requirements), and the feedwater is brackish, RO, MD, and AD would also be suitable to couple with biomass energy.

8. Conclusions

For most scenarios, using renewable energy sources is much more expensive than conventional energy sources due to the high capital cost and the need for energy storage systems. Improvements in energy efficiency and renewable energy collection/conversion technologies have somewhat driven down these costs, and the environmental benefits of using renewable energy sources have helped to shrink the overall advantages of conventional energy systems. However, much more research into optimized site-specific renewable energy-powered water desalination system design is still needed.

Biomass energy can be a suitable source of renewable energy to power brackish water desalination in a hybrid scenario to account for the intermittency of solar and wind, or where there is no viable access to electricity or geothermal energy. Another scenario where larger-scale biomass desalination systems would be feasible is as part of a centralized biomass processing facility where the residual biomass could be used as a fuel.

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