

REVIEW

Synergistic Integration of Hybrid Renewable Energy Systems for Energy-Autonomous Biorefineries: A State-of-the-Art Review

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ABSTRACT: Biorefineries are an important pathway for the sustainable valorization of biomass, especially in rural and resource-distributed regions. However, their economic and environmental performance depends strongly on how energy is supplied to the biorefineries. The use of fossil-based heat and power can reduce their overall sustainability. Integrating renewable energy systems offers a promising alternative. This review examines the technical aspects of the integration of hybrid renewable energy systems (HRES) into biorefineries to achieve energy autonomy. Quantitative analysis identifies thermal operations like drying ($6\text{--}15\text{ MJ kg}^{-1}$) and distillation ($8\text{--}14\text{ MJ kg}^{-1}$) as primary energy sinks, while biochemical processes like fermentation require only $0.8\text{--}2.0\text{ MJ kg}^{-1}$. Integrating concentrated solar thermal systems can achieve solar-to-syngas efficiencies of 20%–35% and reduce internal biomass consumption as a heat source by 33%. The study highlights that solar-assisted systems can increase overall energy efficiency to 54%–75%, significantly higher than the 34% seen in standalone plants. Additionally, wind energy-integrated facilities can reduce greenhouse gas emissions by 92.5%, and advanced solid oxide fuel cell hybrids demonstrate electrical efficiencies up to 63%. Biomass-powered combined heat and power systems integrated with district heating can achieve 70%–90% overall efficiency. However, economic barriers exist, such as a 74% increase in capital costs for certain solar-assisted configurations. The review concludes that decentralized, HRES-powered biorefineries offer a sustainable pathway for regional energy security by overcoming intermittency through synergistic technology integration.

KEYWORDS: Biomass conversion; biorefinery; renewable energy; de-fossilization; circular bioeconomy

1 Introduction

The global transition from a fossil-based economy to a bioeconomy founded on renewable carbon resources has positioned the biorefinery as a key infrastructure for decarbonization. Biorefineries enable the efficient co-production of transportation biofuels, bioenergy, biochemicals, and biomaterials, thereby replacing conventional petrochemical feedstocks with biomass-derived alternatives [1]. From a process

engineering perspective, the concept of a biorefinery closely resembles that of a petroleum refinery. However, instead of crude oil, these systems utilize complex biological feedstocks to generate a diverse range of fuels and value-added products [2]. International organizations have developed standardized definitions to guide the development of biorefinery technologies. The International Energy Agency (IEA) Bioenergy Task 42 defines biorefining as the sustainable processing of biomass into a spectrum of marketable products and energy carriers [3]. This definition aligns with the European Union's (EU) Biorefinery Outlook to 2030, which broadly describes biorefining as the conversion of biomass into a portfolio of marketable bio-based products that may include food and feed, chemicals and materials, and bioenergy in the form of power, heat, cooling, or fuels. The configuration of biorefinery systems depends strongly on the type of feedstock used, which can range from first-generation edible crops to second-generation lignocellulosic residues and third-generation algal biomass, as well as on the selected conversion pathways [1,3,4].

Operationally, biorefineries rely on integrated sequences of unit operations that may occur either sequentially or in parallel. The process generally begins with feedstock pretreatment to improve substrate accessibility, followed by conversion through thermochemical, biochemical, mechanical, or chemical pathways. This integrated platform approach enables the conversion of biomass into a variety of energy carriers, including gaseous fuels such as biogas and hydrogen, liquid fuels such as bioethanol and pyrolysis oil, and solid biofuels such as pellets and biochar [5–8]. In addition to energy products, biorefineries also generate a range of high-value materials, including bulk and specialty chemicals (e.g., organic acids and phenolic compounds), biopolymers, and agricultural inputs such as protein-rich feed and fertilizers [4,9,10]. Despite these advantages, the large-scale commercialization of biorefineries is often constrained by the physical characteristics and spatial distribution of lignocellulosic biomass resources. Unlike fossil fuels, which are typically available in concentrated deposits, biomass is heterogeneous and geographically dispersed. This creates logistical challenges for centralized facilities that require large feedstock volumes, often exceeding 250 kt of dry matter per year, to remain economically viable [11,12]. As a result, the economic benefits associated with economies of scale can be offset by increased transportation costs once biomass sourcing distances exceed approximately 50–100 km. The low bulk density and high moisture content of raw biomass, typically around 30%, further complicate transportation by increasing the cost of moving mass rather than usable energy. In some cases, these factors can increase delivered feedstock costs by up to 50% while negatively affecting the overall energy balance of the system [13,14].

Additional inefficiencies arise when supply chains rely on intermediate storage depots, which often involve multiple handling stages. These double handling practices can increase logistics costs by 10%–20% without adding value to the biomass [15]. To address these techno-economic challenges, recent studies have proposed a transition toward decentralized biorefinery configurations located closer to feedstock sources. Distributed biorefinery systems can reduce transportation costs and improve operational efficiency. Furthermore, decentralized facilities can benefit from thermodynamic synergies, such as the utilization of waste heat from local energy systems to dry biomass. This approach improves feedstock stability by preventing microbial degradation while avoiding additional energy consumption [16,17]. At the same time, fluctuations in fossil fuel markets and the growing urgency to mitigate climate change have accelerated the adoption of renewable energy technologies. However, individual renewable sources often face techno-economic limitations due to their intermittent and location-dependent nature. For instance, solar photovoltaic (PV) systems are widely used in off-grid applications because of their technological maturity, low maintenance requirements, and zero-emission operation. Nevertheless, standalone PV systems often struggle to provide reliable baseload electricity without large and costly energy storage systems [18].

To overcome these limitations while avoiding reliance on diesel generators, which are associated with fuel transport challenges and environmentally harmful emissions, hybrid energy systems have emerged

as an effective solution [19]. Hybrid systems combine multiple renewable energy sources, such as solar, wind, geothermal, or hydropower, to balance fluctuations in power generation. This integration improves system reliability and reduces the required capacity and cost of energy storage technologies [20]. For remote and rural regions, decentralized hybrid microgrids represent a practical alternative to costly grid extension projects. By generating electricity locally, these systems eliminate transmission losses and infrastructure costs while providing reliable energy for agricultural activities and broader socio-economic development [21,22]. Research studies indicate that hybrid energy systems can be economically competitive with conventional fossil-fuel-based systems while offering a scalable pathway toward energy independence in regions that lack access to national power networks [23–26]. Until now, previous reviews on renewable energy integration with biomass conversion and biorefinery have predominantly focused on solar energy [27–29]. Reviews that consider the integration of other renewable sources, such as geothermal and wind energy, as well as hybrid concepts like polygeneration systems for biorefinery, remain limited. In this context, the present study presents a conceptual framework for an energy-autonomous biorefinery based on a comprehensive state-of-the-art review of biorefinery unit operations, their technical aspects, and the integration of renewable energy technologies into biorefinery systems.

2 Methodology for Literature Review

This review adopts the structured methodology (Fig. 1) proposed by Barry et al. (2022), emphasizing transparent literature search procedures, systematic study selection, and thematic synthesis of the major findings [30]. Search queries were developed using combinations of relevant keywords and Boolean operators, including renewable energy, biomass, biorefinery, polygeneration, hybrid energy systems, and power-to-X. A systematic literature search was conducted in Scopus database to identify relevant studies on renewable energy integration in biorefineries. Initially, a broad search using the keyword “biomass” within the Energy subject area, limited to articles and review papers in English, yielded 78,970 documents. To refine the scope, the search was narrowed by incorporating the concept of renewable energy integration, reducing the dataset to 10,681 documents. Subsequently, targeted keyword combinations were applied to capture specific integration pathways. The inclusion of “solar,” “biorefinery,” and “bioconversion” resulted in 166 documents, while similar refinement using “wind” yielded 50 documents. Further narrowing with “geothermal” produced 16 documents, reflecting the relatively limited research in this area. Additional thematic searches were conducted using “polygeneration” (60 documents) and “solid oxide fuel cell” (127 documents) to capture hybrid and advanced energy integration concepts. This stepwise filtering approach enabled the systematic identification of relevant literature encompassing basics of biorefinery unit operations and multiple renewable integration pathways for comprehensive analysis.

The search strategy focused on studies related to energy integration, thermochemical and biochemical conversion technologies. In addition to peer-reviewed journal articles, gray literature and technical reports were examined through targeted searches using Google. Reports published by major international organizations, including IEA Bioenergy, the National Renewable Energy Laboratory (NREL), and the European Commission (EC), were incorporated to capture industrial developments, and recent technological advancements that may not yet be fully represented in academic literature.

Following the literature search, the identified 189 publications were screened according to their relevance to the objectives of this review. Priority was given to studies that addressed: (1) the characterization of thermal and electrical energy demand in biorefinery systems; (2) the integration of renewable energy sources such as solar, geothermal, wind, and bioenergy within biorefinery configurations. The selected articles were then systematically analyzed and categorized based on the type of renewable energy source,

biomass conversion pathway, and system configuration in order to identify key technological developments, integration strategies, and existing research gaps.

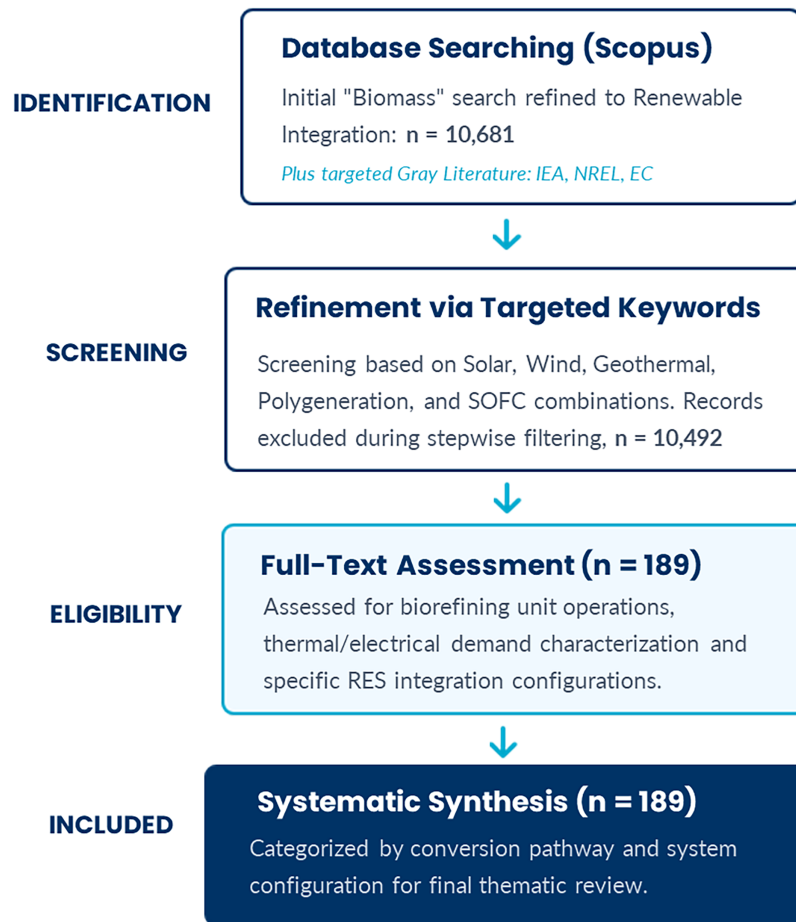


Figure 1: Systematic methodology used for the selection of relevant documents for the review.

3 Thermodynamic and Energy Characterization of Biorefinery Unit Operations

Each unit operation within a biorefinery is controlled by different thermodynamic driving forces, including phase transitions, reaction enthalpy, pressure–volume work, and entropy generation. As a result, the reported specific energy requirements vary considerably across the different stages of the biorefinery value chain. Understanding the underlying mechanisms responsible for these variations is crucial for informed process design, appropriate technology selection, and effective integration with renewable and decentralized energy systems. A comparative overview of the specific energy requirements, thermodynamic characteristics, and their suitability for integration into decentralized Hybrid Renewable Energy Systems (HRES) is summarized in [Table 1](#).

Table 1: Comparative analysis of specific energy requirements, thermodynamic nature, and suitability for integration into decentralized HRES with biorefinery.

Unit Operation	Dominant Energy Vector	Process Conditions (Temperature (T), Pressure (P))	Specific Energy/Utility Req.	Thermodynamic Nature	Suitability for Decentralized HRES	References
Feedstock Drying	Thermal (Q_{low})	60°C–80°C; Atmospheric	Thermal: 3.8–9.5 MJ/kg Bio (87.9% H ₂ O); Elec: Low (fans/conveyors); 3000–9000 kJ/kg water removed	Endothermic. Latent heat of vaporization dominates.	High: Ideal for Solar Thermal Air Collectors or Geothermal waste heat.	[31–34]
Grinding	Electrical (W)	Ambient temperature	Energy use = 3.15 to 8.05 kWh t ^{−1} ; 270–450 kJ/kg of feedstock	Mechanical Work: Highly irreversible process; kinetic energy dissipates as low-grade frictional heat.	Purely electrical load. Creates severe torque spikes (inrush currents) that require battery buffering or robust grid-forming inverters.	[33–35]
Pretreatment (Acid hydrolysis)	Thermal (Q_{High})	160°C–220°C	Thermal: 23.0 to 19.70 MJ/L ethanol	Endothermic to Isothermal: High thermal input required to reach reaction T , maintained isothermally.	Moderate: Requires medium-grade steam (Biomass CHP or Geothermal) and corrosion-resistant alloys, increasing CAPEX for small-scale off-grid setups.	[36,37]
Pretreatment (Steam Explosion)	Thermal (Q_{High})	160°C–220°C; 6–15 bar	Thermal: Energy to generate the total amount of steam = 44 MJ/Kg. Steam energy: 13.55 to 19.33 MJ/L of ethanol	Endothermic. Requires rapid heating to high enthalpy.	Medium: Requires Concentrated Solar Power (CSP) or Biomass Boiler; PV alone is insufficient.	[38,39]

(Continued)

Table 1 (continued)

Unit Operation	Dominant Energy Vector	Process Conditions (Temperature (<i>T</i>), Pressure (<i>P</i>))	Specific Energy/Utility Req.	Thermodynamic Nature	Suitability for Decentralized HRES	References
Enzymatic Hydrolysis	Electrical (<i>W</i>)	45°C–50°C; Atmospheric	Elec: Mixing. Thermal: Low (45°C–50°C maint.). Specific energy consumption (kWh m ⁻³) = 89.3 to 176.1	Isothermal Rheology-driven mixing torque is the primary load.	High: Consistent electrical baseload matches well with Solar PV + Battery.	[40,41]
Fermentation	Electrical (<i>W</i>), Aeration and cooling (<i>Q_{cool}</i>)	30°C–35°C; Atmospheric	Elec: Cooling and Agitation dominant. Total specific power (kWm ⁻³) = 3.27 100 m ³ for a nominal Oxygen transfer rate of 200 mmol. L ⁻¹ h ⁻¹ . Aeration and cooling overall energy demand = 8.5 kW m ⁻³ at 200 mmol L ⁻¹ h ⁻¹ .	Exothermic Metabolic heat generation requires active chilling.	High: Cooling demand often correlates with peak solar irradiance (Solar PV → Chiller).	[42,43]
Distillation (Product Recovery)	Thermal (<i>Q_{med}</i>)	80°C–120°C; Atmospheric/Vacuum	Thermal: 4.2 MJ-fuel/kg-EtOH to 8.5 MJ-fuel/kg-EtOH for a 10 wt% feed	Endothermic: Reboiler duty is the single largest plant energy sink.	Low/Medium: Requires steady-state thermal baseload (Geothermal/Biomass CHP).	[44–46]
Hydrothermal Carbonization (HTC)	Thermal (<i>Q_{med}</i>)	180°C–250°C; 1–5 MPa	Thermal: Start-up only; Elec: Low (stirring). HHV (MJ/kg) of feed = 10–22 MJ/kg; 4.39 to 4.85 heat capacity (kJ·kg ⁻¹ ·K ⁻¹)	Exothermic: Reaction generates heat once initiated (180°C–250°C).	High: Self-sustaining thermally; Ideal for processing wet biomass off-grid.	[47–49]

(Continued)

Table 1 (continued)						
Unit Operation	Dominant Energy Vector	Process Conditions (Temperature (T), Pressure (P))	Specific Energy/Utility Req.	Thermodynamic Nature	Suitability for Decentralized HRES	References
Hydrothermal Liquefaction (HTL)	Thermal (Q_{High}) & Electrical (W)	350°C–400°C; 10–25 MPa	Thermal: High (350–400°C); Elec: High (High P pumping); 6.98 to 13.0 heat capacity ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$); Biooil: 20 and 40 MJ/kg	Endothermic; Heating phase is energy intensive; reaction is complex.	Low: High pressures (10–25 MPa) require grid-quality power stability for safety.	[48,50]
Torrefaction	Thermal (Q_{High}) & Electrical (W)	200°C–300°C	Specific energy consumption reduced from about 237 KWh/t for raw biomass. 130–350 kJ/kg torrefied wood	Endothermic to Exothermic: Initial heating is endothermic; hemicellulose breakdown becomes exothermic.	Very High: volatiles can be combusted to provide the process heat, making the system largely thermally self-sustaining off-grid.	[34]
Slow Pyrolysis	Thermal (Q_{High})	300°C–500°C; Atmospheric	Electrical: Low Thermal: 2.78 MW energy input at 500°C for 1000 kg fresh biomass	Endothermic to Exothermic. Becomes autothermal at $T > 300^\circ\text{C}$.	High: Robust, simple technology; Syngas by-product can run a generator.	[51,52]
Fast Pyrolysis	Thermal (Q_{High})	450°C–550°C; Atmospheric	Thermal: Electrical: Moderate (Fluidization) 50 kWh of energy is required per ton of ground biomass	Endothermic: Requires very high heat transfer rates (500°C in <2 s).	Medium: Needs precise T -control; best paired with Biomass CHP, not variable solar.	[53,54]
Gasification	Thermal (Q_{High})	800°C–1000°C	Thermal: Autothermal (usually). Electrical: High (Air/O ₂ compression) 50 and 150 MW thermal biomass gasifier capacity	Exothermic (Overall)Oxidation zone (>800°C) Drives reduction zone.	Medium/High: Excellent for CHP generation, but tar cleanup adds complexity.	[55,56]
						(Continued)

Table 1 (continued)

Unit Operation	Dominant Energy Vector	Process Conditions (Temperature (T), Pressure (P))	Specific Energy/Utility Req.	Thermodynamic Nature	Suitability for Decentralized HRES	References
Catalytic H_2 Production (SMR/WGS)	Thermal (Q_{High})	700°C–900°C; 20–30 bar	Thermal: Very High; Electrical: Low. $\Delta H_r = -90.64$ kJ/mol at 350°C and 250–350 bar. Dual fluidized bed (50 MW) generates 68 and 87 kg of hydrogen per ton of dry biomass, respectively, with overall energy efficiencies of 59.5% and 64.2%.	Highly Endothermic: Steam Methane Reforming requires 700°C–900°C.	Low: Difficult to sustain high T without natural gas or large-scale CSP fields.	[56–58]
Catalytic Methanol Synthesis	Electrical (W) & Thermal	230°C–270°C; 50–100 bar	Electrical: Very High (Compression); Thermal: Cooling required. $\Delta H_r = -90.64$ kJ/mol. Net power about 100 MW (@ 91% production cap).	Exothermic: Synthesis around 250°C releases heat; Compression around 50+ bar dominates.	Low: Massive parasitic load for gas compression makes off-grid viability poor.	[57,58]
Anaerobic digestion	Electrical (W)	20°C–50°C	Thermal: High heating load to maintain 35°C (Meso) or 55°C (Thermo). Electrical: Low (<10% of output) for mixing/pumping. 5.60 kWh of electricity per 1000 kg “biomass mixture.” 116.49 MJ of heat per 1000 kg “biomass mixture.”	Biochemical: Strictly isothermal requirement. Process is slightly exothermic, but heat losses dominate.	Very High: Produces biogas (storage); acts as a dispatchable baseload generator to balance intermittent solar PV	[59,60]

Because the unit operations in Table 1 report energy in mixed bases (MJ kg^{-1} wet biomass, kWh t^{-1} , MJ L^{-1} ethanol, kWh m^{-3} slurry, etc.) due to non-uniformity of research studies, normalization requires a consistent reference flow, and MJ per kg of dry biomass entering the unit operation was used. Typical assumptions used for cross-comparison were defined to ensure consistency across different conversion processes. These included an initial biomass moisture content of 50–60 wt%, an ethanol yield of 0.25–0.30 L kg^{-1} dry biomass (for biochemical conversion routes), slurry solids loading of 15–20 wt% (relevant to hydrolysis and fermentation processes), a slurry density of approximately 1000 kg m^{-3} , and a boiler efficiency of 80%–85% (for thermochemical systems). For gasification, a large-scale system (50–150 MW thermal) operating under near-autothermal conditions was considered. The biomass input was assumed to be 1 kg on a dry basis, with a higher heating value (HHV) of 15–18 MJ kg^{-1} . The external energy demand was primarily electrical, associated with air or oxygen compression, feed handling, and auxiliary operations. Accordingly, the auxiliary load was estimated at 3%–8% of the total thermal input, corresponding to a parasitic energy requirement of approximately 0.5–1.5 MJ per kg of dry biomass. The general conversion principles used are as follows:

i. Wet to Dry Biomass Basis

$$E_{Dry} = \frac{E_{wet}}{1 - MC} \quad (1)$$

where, MC is the moisture content (mass fraction).

ii. Volume-Based Metrics (e.g., MJ L^{-1} ethanol)

$$E_{MJ/kg \text{ biomass}} = \frac{E_{MJ/L \text{ Product}}}{Y_{product}} \quad (2)$$

where ($Y_{product}$) is the product yield (L ethanol kg^{-1} dry biomass).

iii. Reactor Volume Metrics (kWh m^{-3})

$$E_{MJ/kg \text{ biomass}} = \frac{E_{kWh/m^3} \times 3.6}{\rho_{slurry} \times C_{solids}} \quad (3)$$

Table 2 summarizes the normalized specific energy requirements (MJ kg^{-1} dry biomass) for main biomass processing and conversion unit operations, categorized according to their dominant energy vector (thermal, electrical, or mixed). The results indicate that feedstock preparation and pretreatment stages account for the largest share of total energy consumption, with operations such as drying, steam explosion, and distillation acting as the primary thermal energy sinks. In contrast, processes including enzymatic hydrolysis, fermentation, anaerobic digestion, and hydrothermal carbonization show comparatively lower and more stable energy requirements. These characteristics improve their compatibility with decentralized HRES utilizing solar thermal energy, photovoltaic electricity, biomass combined heat and power, and energy storage technologies. The analysis therefore highlights that energy quality and temporal demand patterns are often more important than total energy consumption when evaluating the feasibility of off-grid biorefinery systems. Based on this perspective, the thermodynamic and energy characteristics of individual biorefinery unit operations are discussed in the following sections.

Table 2: Normalization of energy metrics to MJ kg⁻¹ dry biomass derived from Table 1.

Unit Operation	Normalized Energy Demand (MJ kg ⁻¹ Dry Biomass)	Dominant Vector
Drying	6–15	Thermal (low-grade)
Grinding	0.3–0.6	Electrical
Acid pretreatment	5–8	Thermal (medium/high)
Steam explosion	4–7	Thermal (high-enthalpy steam)
Enzymatic hydrolysis	1.5–3.0	Electrical
Fermentation	0.8–2.0	Electrical (cooling, aeration)
Distillation	8–14	Thermal (reboiler duty)
HTC	1–3 (net, after startup)	Thermal
HTL	10–20	Thermal + Electrical
Torrefaction	1–4 (net, with gas recycle)	Thermal
Slow pyrolysis	2–5 (net)	Thermal
Fast pyrolysis	1–2	Thermal + Electrical
Gasification	0.5–1.5 (net, autothermal)	Thermal + Electrical
Anaerobic digestion	0.5–1.5 (net input)	Thermal (low)

Note: Values represent process input energy, not net system energy balance unless explicitly stated.

3.1 Feedstock Conditioning Operations

3.1.1 Biomass Drying

Drying is a physical separation process used to remove free and bound moisture from biomass through heat-driven evaporation. The transformation occurs via a liquid–vapor phase change within the porous biomass matrix and does not involve chemical reactions. Thermodynamically, the process is governed primarily by the latent heat of vaporization of water, with additional energy losses arising from convective and radiative heat transfer [31,33,34]. Reported specific energy requirements range from approximately 3.0 to 9.5 MJ·kg⁻¹ dry biomass, depending on the initial moisture content, drying technology, and operating conditions. When expressed per unit of water removed, typical values fall within 3000–9000 kJ·kg⁻¹ of evaporated water [32]. Although drying generally operates at relatively low temperatures, typically below 120°C, it exhibits significant thermodynamic irreversibility due to entropy generation associated with phase change and heat transfer. The high energy demand is mainly attributed to the absence of internal heat generation and the conversion of nearly all supplied thermal energy into latent heat rather than chemical transformation. As a result, the latent heat requirement represents a fundamental thermodynamic constraint that establishes a lower bound for energy consumption, explaining why drying remains one of the most energy-intensive operations in biomass processing regardless of technological improvements [31,44]. The energy balance for the biomass drying process can be expressed by the Eq. (4) [61–63].

$$Q_{dry} = m_w \Delta h_{vap} + m_b c_p \Delta T \quad (4)$$

where, m_b is the mass of biomass, c_p is the specific heat capacity, ΔT is the temperature rise, m_w is the water removed, and Δh_{vap} is the latent heat of vaporization.

Since: $\Delta h_{vap} \gg c_p \Delta T$ latent heat dominates [63].

$Q_{dry} \propto (X_i - X_f)$ where X is moisture content.

3.1.2 Grinding and Size Reduction

Grinding is a mechanical pretreatment step used to reduce biomass particle size and increase surface area, thereby improving reactivity and mass transfer during downstream conversion processes. The operation relies on mechanical fracture of biomass particles through impact, compression, or shear forces generated by milling equipment. In thermodynamic terms, grinding converts electrical energy into mechanical work that causes structural deformation of the biomass. Most of this mechanical work is rapidly dissipated as frictional heat due to internal particle friction and equipment resistance. Reported specific energy consumption for biomass grinding typically ranges from 270 to 450 kJ·kg⁻¹ of dry biomass, depending on the type of mill, operating conditions, and the final particle size required [33,35]. Compared with other biorefinery unit operations, grinding has relatively low total energy demand because it does not involve phase transitions, significant temperature changes, or pressurization. However, from a thermodynamic perspective the process is highly irreversible. Nearly all the electrical energy supplied to the mill is degraded into low-grade heat without any useful energy storage within the system.

Consequently, grinding is characterized by significant exergy destruction, as high-quality electrical energy is converted into dissipative heat through friction and particle breakage. The transformation can be represented conceptually as the conversion of electrical work input into heat losses, reflecting the dominance of entropy generation during mechanical deformation. Despite this high exergy loss, the absolute magnitude of energy consumption remains moderate relative to thermal unit operations such as drying or distillation. Grinding therefore represents a purely mechanical unit operation dominated by irreversible work dissipation. The theoretical energy requirement for particle size reduction is often estimated using empirical comminution relationships such as Bond's law, which relates energy consumption to the change in particle size during milling is expressed in Eq. (5) [64–67]:

$$E_g = k_B \left(\frac{1}{\sqrt{d_p}} - \frac{1}{\sqrt{d_f}} \right) \quad (5)$$

where, E_g is specific grinding energy, d_f and d_p are feed and product particle sizes (μm), and k_B is Bond's work index.

3.2 Pretreatment Processes

3.2.1 Acid Pretreatment

Acid pretreatment is widely used to enhance the accessibility of lignocellulosic biomass by hydrolyzing hemicellulose and disrupting the complex biomass structure. The process involves acid-catalyzed reactions that solubilize hemicellulose, producing a cellulose-enriched solid residue and a liquid stream containing dissolved sugars. Although the hydrolysis reactions themselves are slightly exothermic, the primary energy requirement arises from heating the biomass–water slurry to elevated temperatures, typically in the range of 160°C–220°C [68]. The high moisture content of the slurry significantly increases the thermal energy demand because a large fraction of the supplied heat is used for sensible heating of water rather than for chemical transformation. As a result, reported energy requirements for acid pretreatment generally range from 5 to 8 MJ·kg⁻¹ of dry biomass. In integrated biorefinery assessments, this energy consumption is often expressed on a product basis, corresponding to approximately 19–23 MJ per liter of ethanol produced [36,37]. Therefore, the total energy burden of acid pretreatment is largely governed by the thermal energy needed to heat dilute biomass suspensions rather than by the reaction enthalpy of hydrolysis itself.

3.2.2 Steam Explosion Pretreatment

Steam explosion pretreatment exposes biomass to high-pressure saturated steam, followed by sudden depressurization. This rapid pressure release causes structural disruption of the biomass fibers through a combination of thermal softening and mechanical expansion, which increases the accessibility of cellulose for subsequent conversion processes. The process operates at elevated conditions, typically 160°C–220°C and 6–15 bar, requiring the generation of high-enthalpy steam [69]. As a result, steam explosion is considered both energy and exergy-intensive. The energy required for steam generation has been reported to be approximately 44 MJ·kg⁻¹ of steam, which corresponds to about 4–7 MJ·kg⁻¹ of dry biomass, depending on factors such as solids loading and the efficiency of heat recovery systems [39,70]. Consequently, the requirement for rapid heating and pressurized steam explains the comparatively higher energy demand of steam explosion relative to many biochemical pretreatment methods.

3.3 Biochemical Conversion Processes

3.3.1 Enzymatic Hydrolysis

Enzymatic hydrolysis facilitates the conversion of cellulose into fermentable sugars through enzyme-catalyzed cleavage of glycosidic bonds under relatively mild operating conditions. The process typically operates at 45°C–50°C and atmospheric pressure, making it essentially isothermal [71]. The overall energy consumption is primarily associated with mechanical agitation and mixing, which are required to maintain homogeneity and overcome the high viscosity of biomass slurries. Reported energy requirements range from 89–176 kWh·m⁻³ of slurry, corresponding to approximately 1.5–3 MJ·kg⁻¹ of dry biomass [40,41]. The comparatively low energy demand of enzymatic hydrolysis arises from the absence of phase transitions, pressurization, and high-temperature heating, which are common energy-intensive factors in other biomass conversion processes.

3.3.2 Fermentation

Fermentation converts sugars into ethanol (or other bio-products), carbon dioxide, and microbial biomass through microbial metabolic pathways. The process is naturally exothermic, releasing metabolic heat that must be removed to maintain the typical operating temperature of 30°C–35°C [72,73]. Consequently, external energy inputs are mainly associated with electrical power for agitation, aeration, and cooling systems. Reported power requirements generally range from 3 to 9 kW·m⁻³, which corresponds to less than 2 MJ·kg⁻¹ of dry biomass [42,43]. The relatively low net energy demand arises because internally generated metabolic heat partially offsets external heating requirements. From a thermodynamic perspective, the low operating temperature results in a low exergy requirement, and electricity use is largely limited to mixing and aeration. As a result, fermentation is characterized by low normalized energy intensity within the overall biomass conversion process [41]. The heat balance during fermentation is expressed by Eq. (6) [74,75].

$$Q_{net} = Q_{mix} - |\Delta H_{ferm}| \quad (6)$$

where: ΔH_{ferm} (heat released during glucose fermentation) could be –101.28 kJ·mol⁻¹ for anaerobic fermentation and –231.27 kJ·mol⁻¹ for aerobic fermentation. The enthalpy changes depending on metabolic pathways and biomass formation [76].

3.3.3 Anaerobic Digestion

Anaerobic digestion converts wet biomass into biogas through a sequence of microbial processes, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The biochemical reactions are slightly

exothermic, but external heat is generally required to offset thermal losses and maintain stable operating temperatures under mesophilic (35°C–40°C) or thermophilic (50°C–55°C) conditions [77]. Typical energy inputs are reported at approximately 5.6 kWh of electricity and 116 MJ of heat per 1000 kg of wet feedstock, which corresponds to roughly 1–2 MJ·kg⁻¹ of dry biomass, depending on substrate solids content [59,60]. A major advantage of anaerobic digestion is the generation of biogas as a dispatchable chemical energy carrier, which can balance process energy demand and provide additional energy services. In practice, most external energy requirements occur during system start-up and temperature stabilization. This characteristic makes anaerobic digestion highly compatible with decentralized bioenergy systems, where produced biogas can be directly utilized for heat, electricity generation, or upgrading to biomethane [59,60]. The energy balance for anaerobic digestion can be represented by Eq. (7) [78–82].

$$Q_{AD} = Q_{heat-up} + Q_{loss} - |\Delta H_{AD}| \quad (7)$$

where: $Q_{heat-up}$ = heat required to raise the feed to operating temperature, Q_{loss} = heat losses to the surroundings, $|\Delta H_{AD}|$ = heat released from anaerobic digestion reactions. At steady state: $|\Delta H_{AD}| \approx Q_{loss}$

3.4 Separation and Purification

Distillation

Distillation is used to separate ethanol from dilute fermentation broths through repeated cycles of vaporization and condensation, controlled by vapor–liquid equilibrium. From a thermodynamic perspective, the process is dominated by the latent heat of vaporization and is inherently irreversible [83,84]. Reported thermal energy requirements range between 4.2 and 8.5 MJ per kg of ethanol, which corresponds to approximately 8–14 MJ per kg of dry biomass at typical fermentation concentrations [44–46]. Since the process lacks internal heat generation, distillation represents one of the most energy-intensive operations in a biorefinery.

3.5 Thermochemical Conversion Processes

3.5.1 Torrefaction

Torrefaction is a mild thermal treatment of biomass carried out at 200°C–300°C, in which hemicellulose undergoes weak exothermic decomposition [85]. The process requires initial heat input to reach operating temperature, after which the release of volatile compounds can partially sustain the reaction, allowing near-autothermal operation [34]. The energy balance for torrefaction can be described by Eq. (8) [86–88].

$$Q_{tor} = mc_p \Delta T - |\Delta H_{hemi}| \quad (8)$$

where, Q_{tor} is net external heat required for torrefaction, $mc_p \Delta T$ is external heat input (sensible heating) and $|\Delta H_{hemi}|$ is heat released from hemicellulose decomposition.

3.5.2 Hydrothermal Carbonization

HTC transforms wet biomass into a carbon-rich solid, known as hydrochar, through dehydration and decarboxylation in hot, pressurized water. While initial heating is necessary to reach reaction conditions, the process is largely exothermic, allowing for partial self-sustaining operation. HTC generally conducted at 180°C–250°C and 1–5 MPa, and consumes 1–3 MJ per kilogram of dry biomass when heat recovery is applied [47–49]. Its moderate operating conditions and internal heat generation contribute to its relatively low net energy requirement.

3.5.3 Hydrothermal Liquefaction

HTL converts wet biomass into bio-crude oil under near-critical water conditions. HTL operates at 350°C–400°C and 10–25 MPa, leading to substantial sensible heating and compression work. Reaction enthalpy is insufficient to offset these inputs, resulting in reported net energy demands of 10–20 MJ kg⁻¹ dry biomass, even with heat recovery [48,50]. High operating severity is the principal reason for HTLs elevated energy intensity.

3.5.4 Pyrolysis

Pyrolysis decomposes biomass thermally in the absence of oxygen. Despite operating at elevated temperatures (300°C–1000°C), pyrolysis can achieve near-autothermal operation by partially combusting the feedstock or produced gases. External energy requirements are typically in the range of 2–5 MJ per kilogram of dry biomass [54,55], with internal heat generation helping to offset high sensible heat demands. In slow pyrolysis, the process is initially endothermic during early decomposition, but exothermic char formation partially compensates for the heat input, and the generated syngas can further supply process energy (Cherubini et al., 2009). The energy balance for slow pyrolysis can be represented by the simplified Eq. (9) [89–91].

$$Q_{slow} = Q_{heat-up} + Q_{loss} - |\Delta H_{char}| \quad (9)$$

where, Q_{slow} represents the net external heat required to carry out the slow pyrolysis process. $Q_{heat-up}$ is dominant energy input (sensible heating), Q_{loss} is the heat loss, and $|\Delta H_{char}|$ is heat released due to char formation reactions.

Fast pyrolysis involves very high heat transfer rates, with rapid heating times of less than 2 s. Electrical energy is needed for fluidization, leading to moderate to high exergy consumption. Due to the highly endothermic nature of the process and rapid heating requirements, external heat supply is essential to sustain reactor operation. The heat requirement for fast pyrolysis can be determined by the Eq. (10) [54,89,92,93].

$$Q_{fast} = mc_p (T_{op} - T_0) + Q_{loss} \quad (10)$$

where, Q_{fast} is the total external heat required for fast pyrolysis, m is mass of biomass (kg), c_p is the specific heat capacity of biomass, T_{op} is the operating temperature (typically 450°C–550°C), T_0 is the initial temperature (ambient), and Q_{loss} is the heat losses to surroundings (reactor inefficiencies).

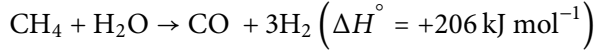
3.5.5 Gasification, Hydrogen and Methanol Production

Gasification is overall exothermic but requires high-temperature operation (800°C–1000°C). Oxidation zone supplies heat, and electricity is required for compression and gas cleanup [34,55]. The net energy balance for gasification can be calculated by the Eq. (11) [89,91,94].

$$Q_{gas} = Q_{heat-up} + Q_{air} - |\Delta H_{ox}| \quad (11)$$

where, Q_{gas} is the net external heat required for gasification, $Q_{heat-up}$ is the heat required to raise biomass to gasification temperature, Q_{air} is the energy associated with air/oxidant supply (includes sensible heat and compression) and $|\Delta H_{ox}|$ is the heat released from partial oxidation/combustion reactions. In autothermal gasification, the heat generated from oxidation reactions can sufficiently sustain the endothermic gasification reactions, resulting in negligible external heat demand. Biomass gasification is widely used to produce hydrogen and methanol from syngas.

Hydrogen production operates at elevated temperatures (700°C–900°C) and requires high-exergy heat. The total energy demand increases with the targeted hydrogen yield, as the process is strongly endothermic and dictated by reaction thermodynamics [57,58]. The reaction enthalpy can be expressed as follows [91,94]:



The energy requirement for hydrogen production can be determined by Eq. (12) [89,91,94]:

$$Q_{\text{H}_2} = Q_{\text{sensible}} + Q_{\text{rxn}} + Q_{\text{loss}} \quad (12)$$

where, Q_{H_2} is the total energy requirement for hydrogen production, Q_{sensible} is the sensible heat required to raise the temperature of reactants (e.g., biomass, steam, gases) to the operating temperature, Q_{rxn} is the heat of reaction, and Q_{loss} is the heat losses due to radiation, convection, and reactor inefficiencies.

Methanol synthesis is exothermic, but energy-intensive due to gas compression. The reaction for methanol synthesis from carbon monoxide and hydrogen gases is represented by following equation:



The reaction itself is exothermic, but the energy input is primarily driven by compression, which requires substantial electricity and high-exergy input [57]. The work associated with compression can be expressed by Eq. (13) [95]:

$$W_{\text{comp}} = \frac{RT}{\eta} \ln \left(\frac{P_2}{P_1} \right) \quad (13)$$

where, W_{comp} is the specific compression work ($\text{kJ} \cdot \text{mol}^{-1}$), R is the universal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is the absolute temperature (K), η is the compressor efficiency (isentropic or mechanical, dimensionless), P_1 is the initial pressure and P_2 is the final pressure.

3.6 Thermodynamic Origins of Energy Demand Differences

Variations in energy requirements among biorefinery unit operations stem from four main thermodynamic factors:

3.6.1 Phase Change Requirements

Biorefinery unit operations that rely on evaporation or condensation, such as biomass drying and ethanol distillation, are inherently energy-intensive because they are dominated by the latent heat of phase change rather than by chemical reaction energy. Energy must be supplied to overcome intermolecular forces during the liquid-to-vapor transition without altering the material's chemical composition. Thermodynamically, the latent heat of vaporization, approximately $2257 \text{ kJ} \cdot \text{kg}^{-1}$ for water at 100°C or $846 \text{ kJ} \cdot \text{kg}^{-1}$ for ethanol at its boiling point, sets an unavoidable minimum energy requirement that cannot be reduced through process optimization alone [44]. In practice, actual energy use exceeds this theoretical minimum due to heat losses, non-ideal vapor–liquid equilibria, and the repeated vaporization–condensation cycles typical in multistage distillation systems. These phase-change operations are highly irreversible, with significant entropy generation when heat is supplied across finite temperature differences. Consequently, even with low-temperature heat sources, drying and distillation remain major thermal energy demands in biorefineries. The

minimum theoretical heat requirement for such phase-change processes can be expressed by Eq. (14) [31,91].

$$Q_{\min} = m_{\text{vap}} \Delta H_{\text{vap}} \quad (14)$$

where, $Q_{\min}$ is the minimum theoretical heat required for evaporation, m_{vap} is the mass of vaporized water, ΔH_{vap} is the latent heat of vaporization.

In biomass drying, the sensible heat term is negligible relative to latent heat:

$$Q_{\text{dry}} \approx m_{\text{water}} \Delta H_{\text{vap}} \gg m_{\text{solid}} c_p \Delta T$$

where, Q_{dry} is the total heat required for drying, m_{water} is the moisture removed from biomass, m_{solid} is the dry biomass mass, c_p is the specific heat capacity of biomass, ΔT is the temperature rise. This defines a fundamental thermodynamic limit for energy consumption that cannot be lowered through process intensification. As a result, drying and distillation consistently show high normalized energy requirements ($\text{MJ} \cdot \text{kg}^{-1}$ dry biomass) regardless of the scale or technology employed [44].

3.6.2 Operating Severity (Temperature and Pressure)

Thermochemical conversion processes such as HTL and gasification operate under high-severity conditions, which involve elevated temperatures and pressures, resulting in substantially higher energy requirements than biochemical routes [48]. Energy consumption in these systems is primarily driven by the large sensible heat needed to raise water-rich biomass slurries to reaction temperatures (e.g., 350°C – 400°C for HTL) and the additional compression work required to maintain pressures of 10–25 MPa. Unlike biochemical operations conducted near ambient conditions, high-severity thermochemical processes must overcome both thermal inertia and mechanical resistance. Heat recovery is also less efficient at extreme conditions due to material limits, fouling, and heat exchanger constraints, leaving a significant portion of supplied energy unrecovered. Consequently, net energy consumption is considerably higher than in low-temperature biochemical pathways [96]. For thermochemical conversion routes such as HTC, HTL, and gasification, the dominant energy input during heat-up is [97,98]:

$$Q_{\text{sensible}} = mc_p (T_{\text{op}} - T_0) \quad (15)$$

Biomass slurries exhibit high effective heat capacities: $c_p^{\text{slurry}} \approx 3.5 - 4.5 \text{ kJ kg}^{-1} \text{K}^{-1}$.

Therefore, raising the operating temperature from HTC (200°C) to HTL (375°C) results in a substantial increase in energy demand, even without considering the additional effects of pressure [98,99].

High-pressure processes require continuous mechanical energy input, presented in Eq. (16) [97,100,101]:

$$W_{\text{pump}} = \frac{\Delta P \dot{V}}{\eta} \quad (16)$$

where W_{pump} is mechanical energy required to pressurize and transport the fluid, ΔP is difference between outlet and inlet pressure, $\dot{V}$ is volumetric flow rate, and η is pump efficiency. In HTC systems operating at 15–25 MPa, the energy required for compression is significant. In contrast, HTC usually functions at near-autogenous pressures of 2–5 MPa, which accounts for the roughly tenfold difference in normalized energy consumption between these two hydrothermal processes [48].

3.6.3 Internal Heat Generation

Exothermic or autothermal processes such as fermentation, anaerobic digestion, HTC, gasification and certain pyrolysis systems can partially or completely compensate for external energy requirements because they generate heat internally during the conversion reactions [34,59]. The presence of internal heat production significantly influences the external energy demand of a biorefinery unit operation. In biochemical processes like fermentation and anaerobic digestion, microbial metabolism converts complex organic compounds into lower-energy products such as ethanol, methane, and carbon dioxide, releasing heat in the process. Although some external heat input may still be required to maintain optimal operating temperatures, the heat generated by these metabolic reactions contributes to the process energy balance, resulting in relatively low net external energy demand [59]. Similarly, HTC involves dehydration and decarboxylation reactions that are generally exothermic, allowing the process to achieve partial thermal self-sufficiency after reaching its operating temperature. In thermochemical systems such as pyrolysis and gasification, heat can be produced by deliberately oxidizing or combusting a small fraction of the feedstock, helping sustain reactor temperatures and enabling the process to approach autothermal operation [34]. In contrast, processes that do not generate internal heat such as drying and distillation depend entirely on externally supplied energy, which explains their comparatively higher net energy requirements. The external energy requirement of a unit operation can be presented in Eq. (17) [102–104]:

$$Q_{net} = Q_{heatup} + Q_{loss} - |\Delta H_{rxn}| \quad (17)$$

where Q_{net} is net external energy requirement, Q_{heatup} is sensible (and latent) heat of the feed, Q_{loss} is heat loss to the surroundings, and ΔH_{rxn} is absolute enthalpy of reaction (heat of reaction). Processes such as anaerobic digestion, fermentation, and HTC exhibit exothermic or weakly endothermic reaction pathways ($\Delta H_{rxn} \leq 0$). If, $|\Delta H_{rxn}| \geq Q_{loss}$ the system approaches autothermal operation, requiring energy input only during start-up. This explains why biochemical and mild hydrothermal processes consistently exhibit low steady-state energy intensities (1–5 MJ kg⁻¹ dry biomass) [49,59].

3.6.4 Energy Quality (Exergy) Requirements

Exergy refers to the maximum useful work that can be obtained from an energy source relative to its surrounding environment [105,106]. Operations that depend on electricity or high-pressure steam, such as grinding, steam explosion, and HTL, require high-quality energy inputs that are typically more expensive and difficult to supply, particularly in decentralized or renewable-based systems. Electricity, as one of the highest-quality energy carriers, experiences substantial exergy losses when it is ultimately converted into low-grade heat or dissipated as mechanical losses [41]. By contrast, processes that can operate with low-temperature thermal energy such as drying, enzymatic hydrolysis, temperature regulation in fermentation, and anaerobic digestion can take advantage of low-exergy heat sources like solar thermal energy, geothermal heat, or industrial waste heat. Even when the total energy requirement is moderate, the ability to use lower-quality heat significantly enhances system efficiency and facilitates integration with renewable or residual energy streams. Consequently, processes with high exergy demands place considerably greater pressure on energy systems than those with comparable energy consumption but lower exergy intensity [105,107]. The usable work potential of heat is limited by Carnot efficiency, which is presented in Eq. (18) [108,109]:

$$Ex_Q = Q \left(1 - \frac{T_0}{T} \right) \quad (18)$$

In Eq. (18), Ex_Q is the exergy of heat, Q is Heat supplied, T is source temperature, and T_0 is the ambient temperature (typically 298 K). Low-temperature heat (e.g., 60°C–80°C drying air) has low exergy,

even when energy quantities are large [105,107]. Using electricity for low-value thermal operations (e.g., grinding, mixing) results in high exergy destruction. This is the reason for mechanical work being so energy-inefficient, even when their total absolute energy consumption seems low [41]. Collectively, phase change requirements, process severity, internal heat generation, and energy quality account for the large differences in energy demand observed among unit operations. Processes such as distillation, HTL, and steam explosion repeatedly appear as major energy bottlenecks because they involve phase transitions, high temperatures or pressures, and high-quality energy inputs. In contrast, biochemical conversions and milder thermochemical processes typically require much lower net external energy. Understanding these thermodynamic drivers provides a useful framework for evaluating and prioritizing technologies, particularly when designing hybrid biorefineries intended to integrate renewable energy sources.

4 Renewable Energy Technologies Integrated with Biorefineries

4.1 Solar Power Integration

4.1.1 Solar-Assisted Biomass Gasification Systems

The use of solar energy in biomass gasification systems has gained attention as an effective strategy to improve both the energy efficiency and environmental performance of thermochemical biorefineries. The research studies on the integration of solar energy into biomass gasification systems are presented in Table 3. In traditional autothermal gasification, a portion of the biomass feedstock is burned to supply the heat required for the endothermic gasification reactions [110]. Contrastingly, concentrated solar thermal (CST) systems can provide the high-temperature heat needed to drive endothermic gasification reactions, thereby reducing the reliance on internal biomass combustion and enhancing energy conversion efficiency. This substitution enables a greater share of the biomass carbon to be converted into useful syngas constituents, particularly CO and H₂ [111,112]. The main endothermic reactions ($C + H_2O \rightarrow CO + H_2$; $\Delta H^\circ_{298} = +131 \text{ kJ mol}^{-1}$) involved in steam gasification particularly benefit from the direct supply of solar thermal energy, which reduces greenhouse gas emissions while enhancing chemical energy retention in the product gas and improving the overall thermodynamic efficiency of the process [111,113].

Studies report solar-to-syngas conversion efficiencies typically ranging from about 20% to 35%, depending on factors such as reactor configuration, the proportion of solar heat used, and operating conditions [114]. Experimental and modeling studies have demonstrated the feasibility of solar gasification across multiple reactor configurations. Early experimental work showed that cavity-type solar reactors could achieve temperatures above 1200°C with solar inputs of only a few kilowatts, enabling significant biomass conversion and reduced tar formation [115]. In on-sun tests, biomass conversion reached approximately 68%, with carbon conversion to CO and CO₂ averaging 58.4%. Similarly, solar steam gasification experiments conducted using concentrated solar radiation demonstrated high hydrogen yields and gasification efficiencies exceeding 60% for real biomass feedstocks [116]. Reactor design plays a critical role in determining system performance. Various solar gasifier concepts including packed-bed, vortex-flow, and entrained-flow reactors have been investigated to optimize heat transfer and reaction kinetics. Packed-bed designs offer flexibility for different biomass feedstocks, while entrained-flow reactors provide superior heat and mass transfer characteristics [117]. Modeling studies have further demonstrated that incorporating temperature gradient theory and improved heat transfer mechanisms can enhance energy conversion efficiency by more than 20%, achieving overall efficiencies up to 55% in solar downdraft gasifiers [118]. Scaling analyses indicate that larger solar reactors can achieve even higher solar-to-chemical conversion efficiencies due to improved radiative heat absorption and reduced relative heat losses. Simulations of multi-tube solar cavity reactors predict peak efficiencies of 39% for 100 kW systems and up to 50% for 1 MW configurations under optimized feed rates [119]. Nevertheless, re-radiation losses from the cavity aperture remain a major

source of thermodynamic irreversibility, highlighting the need for improved receiver designs and advanced high-temperature materials.

Hybrid solar–biomass systems have also been proposed to overcome solar intermittency while maintaining high energy efficiency. Hybrid solar/autothermal gasification systems can operate in fully solar-driven, autothermal, or combined modes depending on solar irradiance levels. Dynamic modeling studies show that such systems can maintain stable reactor temperatures with minimal fluctuations, achieving solar-to-fuel efficiencies of approximately 39% during full solar operation and cold gas efficiencies of around 87% during autothermal operation [120]. These hybrid configurations enable continuous syngas production while storing solar energy in chemical form. Integration of solar heat with biomass gasification can also significantly improve the overall efficiency of CHP and polygeneration systems. For example, hybrid solar gasifiers integrated with gas turbine systems have demonstrated electrical efficiencies between 25% and 40%, with total system efficiencies reaching 40%–60% when waste heat recovery is included [114]. In addition, solar-hybrid gasification systems can increase syngas heating value by more than 50% due to enhanced production of CO and H₂ [121].

Large-scale system studies further confirm the energy advantages of solar integration. A solar-hybridized dual fluidized bed gasifier operating at 50 MW_{th} achieved energy conversion efficiencies between 60% and 73%, surpassing conventional biomass cogeneration benchmarks [122]. Similarly, conceptual designs for solar-driven biomass-to-liquid fuel systems indicate that integrating concentrated solar heat can reduce biomass consumption by up to 33% while maintaining comparable fuel outputs [123]. These improvements result from replacing combustion heat with renewable solar energy, thereby preserving more biomass carbon for fuel synthesis. Gutiérrez et al. (2022) evaluated a 500 MW_{th} CSP-assisted thermochemical biorefinery producing dimethyl ether (DME) from gasified biomass. Integration of a 50 MW_e CSP system with 15 h thermal energy storage enabled partial substitution of combustion heat, supplying up to 85% of internal electricity demand and allowing electricity exports equivalent to 52% of the annual plant demand. The addition of CSP improved fuel upgrading efficiency by 2%–4%, although the overall plant efficiency declined by up to 11 percentage points due to the low electrical efficiency of CSP (~16%). CSP integration increased capital costs by approximately 74% and raised DME selling prices to 18.3–21.2 USD GJ^{−1}. Despite the cost penalty, CSP-assisted integration reduced exposure to biomass and electricity price volatility, supporting operational robustness under high-renewable grid conditions [29].

Table 3: Studies on the integration of solar energy for biomass gasification.

Reactor/System Type	Scale	Key Energy Parameters	Main Findings	References
Solar-driven biomass gasification + electrolysis	Conceptual	~90% carbon utilization; reduced biomass input (~33%)	Solar integration reduces biomass demand, near-complete carbon utilization	[124]
Solar cavity receiver, multi-tube	3 kW ^{−1} MW	Solar-to-chemical efficiency 39%–50%	Demonstrated scalability and energy conversion potential	[119]

(Continued)

Table 3 (continued)

Reactor/System Type	Scale	Key Energy Parameters	Main Findings	References
Solar cavity reactor	7.5 kW	Temperatures >1200°C; biomass conversion 68%	High-temperature solar gasification improves conversion and syngas quality	[115]
Solar-driven SCW gasification	Lab-scale	H ₂ fraction 41%–50%; gasification efficiency up to 64.9%	Hydrogen-rich syngas production feasible	[116]
Solar downdraft gasifier	Model	Energy efficiency up to 55%	Hydrogen-dominant syngas; improved conversion via temperature gradients	[118]
Packed-bed, vortex, entrained-flow solar reactors	Pilot	Syngas calorific value +33%	Multiple viable reactor designs; feedstock flexibility	[117]
BFB gasifier + CSTP	Pilot	Efficiency improved via heat integration	Hybrid operation enhances overall performance, efficiency plateau at high solar input	[125]
Solar/autothermal hybrid gasifier	Pilot	Solar-to-fuel efficiency ~39%; autothermal cold gas efficiency 87%	Hybrid operation ensures stable syngas production under variable irradiance	[120]
SAHG + ICE-based CCHP	Pilot	Syngas LHV +51.7%; primary energy ratio +11.5%	Solar upgrading improves system energy performance	[121]
Solar-hybrid DFB gasifier	50 MWth	Overall efficiency 60%–73%; CO ₂ reduction ~17%	Enhanced energy output and negative emissions potential	[122]
500 MWth CSP-assisted DME biorefinery	50 MWe CSP	Fuel upgrading efficiency 2%–4%	CSP reduces biomass/electricity exposure; high capital cost; electricity exportable	[29]

4.1.2 Solar-Assisted Biomass Pyrolysis

Studies on the integration of solar energy with pyrolysis systems are summarized in Table 4. High-flux solar reactors, including solar furnaces and parabolic dish concentrators, can deliver solar fluxes exceeding

12,000 kW m⁻², enabling rapid heating rates of approximately 50°C s⁻¹ [126]. These conditions are suitable for driving thermochemical reactions in fast pyrolysis while minimizing external fuel consumption. Fast pyrolysis has been investigated within hybrid renewable energy systems that integrate biomass conversion with solar photovoltaic electricity generation. Such systems can improve energy reliability by combining intermittent solar generation with dispatchable bioenergy. Modeling work by Perkins (2018) examined a distributed fast pyrolysis facility processing approximately 16 t d⁻¹ of biomass. The plant produced around 50 barrels per day (bpd) of biocrude and generated roughly 17 MWh d⁻¹ of electricity. In the modeled configuration, solar PV provided between 38% and 50% of the plant's electricity demand, while the combustion of stored biocrude supplied the remaining energy required for continuous operation. Energy storage was achieved through biocrude accumulation, which reached approximately 14 MWh of stored energy capacity, enabling the system to shift electricity production across daily demand cycles. Under scenarios with constant electricity demand rather than peak-based loads, biomass throughput increased to approximately 28 t d⁻¹, resulting in biocrude production of about 90 bpd and power generation of roughly 1.3 MWe. These results highlight an important characteristic of bioenergy systems: the scale of dispatchable power production is primarily determined by average demand rather than peak load. Consequently, distributed pyrolysis facilities can be designed to provide flexible renewable power generation while maintaining stable biomass supply chains [127,128].

Experimental studies have demonstrated that solar-assisted pyrolysis can improve product quality. For instance, the solar pyrolysis of beech wood was shown to reduce the water content of produced bio-oil by approximately 15%, thereby improving its calorific value and fuel properties [129]. Despite these advantages, product yields remain strongly influenced by feedstock composition, particle size, and reactor hydrodynamics. Investigations into feedstocks such as jatropha biomass have highlighted the importance of optimizing reactor design and operational parameters to achieve stable performance and desirable product distributions [130,131]. Further improvements in fuel quality can be achieved through catalytic fast pyrolysis (CFP), in which catalysts promote partial deoxygenation of bio-oil vapors during the pyrolysis process. This upgrading step reduces oxygenated compounds in the produced biocrude, improving its stability and compatibility with conventional fuel infrastructure. However, catalytic processes also generate by-products such as coke deposits and non-condensable gases. These secondary streams can be integrated into energy recovery systems through gasification or combustion, producing additional heat and electricity. In hybrid renewable energy systems, this approach enables the simultaneous generation of baseload electricity from pyrolysis by-products while reserving stored biocrude for peak electricity demand. Such configurations can create fully renewable and dispatchable power systems capable of supporting grid stability [127,128]. At the system level, distributed solar-assisted pyrolysis plants offer several economic and operational advantages. Electricity generation can begin immediately from pyrolysis by-products and biocrude combustion, providing revenue before large-scale fuel upgrading infrastructure is deployed. This staged development approach reduces financial risk and allows gradual expansion of plant capacity as market conditions evolve. Moreover, modular system designs allow additional solar PV capacity or energy storage systems to be incorporated over time.

Table 4: Studies on biomass pyrolysis systems integrated with solar energy.

Pyrolysis Type	Temperature Range	Main Products	Energy Characteristics	Main Advantages	Major Challenges	References
Slow Pyrolysis	350°C–500°C	Biochar, gases, small fraction of bio-oil	60%–75% of feedstock energy retained in biochar	High carbon retention, suitable for carbon sequestration and solid fuel	Lower liquid fuel yield	[34]
Fast Pyrolysis	450°C–550°C	Bio-oil (60–70 wt%), gases, char	High conversion to liquid fuel	Energy-dense liquid fuel suitable for storage and transport	Requires high heating rates and precise temperature control	[34]
Solar-Assisted Pyrolysis	~450°C–550°C (solar-heated)	Bio-oil with improved quality	Solar flux up to 12,000 kW m ⁻² enabling ~50°C s ⁻¹ heating	Reduced fossil energy input, improved bio-oil properties	Reactor complexity, dependence on solar availability	[129]
Catalytic Fast Pyrolysis (CFP)	450°C–550°C with catalyst	Upgraded biocrude, gases, coke	Partial deoxygenation improves fuel quality	Improved fuel stability and compatibility with refining	Catalyst deactivation and coke formation	[127]
Solar PV–Fast Pyrolysis Hybrid Systems	Integrated energy system	Electricity + biocrude storage	~17 MWh d ⁻¹ electricity from 16 t d ⁻¹ biomass; PV supplies 38%–50% electricity	Dispatchable renewable power with energy storage	Capital cost and system integration complexity	[127,132]

Sustainability assessments have also been conducted to evaluate the environmental performance of integrated solar–pyrolysis energy systems. Using emergy analysis, Cheng et al. (2020) examined a pilot hybrid solar-pyrolysis energy system (HSPES) utilizing apple wood as the primary biomass feedstock. The total emergy input to the system was estimated at 6.90×10^{15} seJ yr⁻¹, with purchased resources accounting for approximately 99.85% of the input. Renewable resources contributed 63.51% of the total emergy, reflecting strong dependence on solar radiation and biomass availability. During system operation, the dominant inputs included apple wood (38.35%), electricity (28.59%), and labor (25.02%). The pyrolysis subsystem played the primary role in energy conversion, with total input and output emergy values six and nine times greater than those of the solar subsystem, respectively. Several emergy-based performance indicators were calculated to evaluate system sustainability. The transformity of the produced energy was estimated at 7.45×10^4 seJ J⁻¹, while the emergy yield ratio, environmental loading ratio (ELR), and emergy sustainability index were 2.78, 0.57, and 1.74, respectively. These values indicate relatively efficient resource utilization, low environmental pressure, and moderate long-term sustainability potential. However, it should be noted that emergy-based indicators depend on system boundaries and conversion factors, which may limit direct comparability with other assessment approaches. The analysis also revealed a limited contribution from locally available resources, suggesting that further improvements in regional biomass supply chains could enhance system resilience [132].

4.1.3 Solar Assisted Hydrothermal Systems

Laboratory-scale studies under solar-relevant conditions have demonstrated the feasibility of HTL for diverse organic wastes. Tsongidis et al. (2022) investigated peach stones, food waste, and dairy waste at 300°C and a 30-min retention time, varying the water-to-feedstock ratio to assess its effect on yields. Results indicated that dairy waste produced the highest biocrude yield (~22 wt%), and increasing the water ratio enhanced yields by up to 98%, underscoring water's dual role as a solvent and reactive medium. These findings suggest strong synergy between HTL and CST systems, which can supply the required process heat while improving energy efficiency and sustainability. Compared to high-temperature thermochemical routes, hydrothermal systems operate at moderate temperatures, making them more amenable to coupling with solar thermal collectors and reducing the scale of required solar fields for process heat provision [34,114]. Moreover, the liquid products of HTL, biocrudes could provide an energy-dense, transportable fuel that can be further upgraded or used for on-site electricity generation, enhancing operational flexibility.

Techno-economic analyses of solar-assisted lignocellulosic ethanol biorefineries reinforce the energy advantages of solar integration. Nwai and Patel (2023) examined multiple corn stover-to-ethanol configurations in South Africa, highlighting that standalone biorefineries relying on lignin combustion achieved ~34% overall energy efficiency, whereas solar-assisted systems combining CSP, solar PV, and solar thermal heat, alongside lignin valorization, increased overall efficiency to 54%–75%. Thermal utilities accounted for more than 80% of process energy demand, emphasizing the critical role of solar thermal integration. Heat integration further reduced gross energy requirements from 29.4 to 19.6 MJ kg⁻¹ ethanol, demonstrating that low- and medium-temperature solar heat can significantly enhance system energy performance [133]. Pilot-scale solar-assisted biorefineries have further validated the technical feasibility of coupling renewable heat with wet biomass conversion. Golberg (2021) reported a 10-t h⁻¹ solar-seaweed biorefinery in Israel, achieving a First-Law efficiency of 32%, which increased to over 40% with waste-stream recycling. The facility produced 6.1 MW of electricity alongside hydrochar, protein concentrates, ethanol, and water products. Economic performance was sensitive to protein and electricity prices, while environmental impacts were minimized through optimized logistics and partial PV integration [134].

Large-scale solar-driven hydrothermal systems follow a fundamental scaling principle wherein the required solar field area increases linearly with process heat demand and solar multiple (SM), as represented in Eq. (19) [134]:

$$A_{field} = \frac{\dot{Q}_{process} \times SM}{DNI \times \eta_{optical} \times \eta_{thermal}} \quad (19)$$

where field area increases linearly with process heat demand and solar multiple.

Consequently, high-temperature gasification-based systems require substantially larger heliostat fields than lower-temperature hydrothermal platforms, making HTL and HTC more favorable for decentralized or semi-distributed applications where land availability and capital costs are constraints. Additionally, emerging PV-coupled electrocatalytic upgrading methods offer non-thermal pathways for chemical conversion under mild conditions (<80°C). While requiring 6–10 kWh kg⁻¹ product, solar-powered electrocatalytic processes can achieve life-cycle emissions below 15 g CO₂-eq MJ⁻¹, providing complementary strategies for integrating solar electricity with hydrothermal conversion [135].

4.2 Geothermal and Wind Energy Integration

Geothermal and wind energy are particularly promising due to their complementary characteristics: geothermal provides continuous, high-quality thermal energy, while wind delivers flexible electricity to fully

or partially electrified processes. The combination of these resources enables biorefineries to achieve stable, low-carbon operation across diverse biochemical and thermochemical conversion pathways. Geothermal energy is well-suited for supplying baseload process heat in biorefineries, especially where low to medium-enthalpy resources are locally available. A summary of studies on the integration of geothermal and wind energy into biorefineries is presented in Table 5. By substituting geothermal heat for internal biomass combustion, lignin-rich residues can be redirected to higher-value products such as chemicals, materials, or upgraded biofuels, thereby improving overall resource efficiency [136]. Early system-level assessments demonstrated that integrating geothermal heat enhances lignin recovery, increases electricity self-sufficiency, and preserves biomass carbon for value-added applications rather than dissipating it through low-efficiency thermal processes. Sohel and Jack (2010) highlighted these benefits across multiple operational objectives, including maximizing lignin production, maximizing electricity output, and balancing lignin recovery with electricity generation [136].

Techno-economic analyses substantiate above findings. Banerjee et al. (2013) investigated a 2000 t-day⁻¹ corn stover biorefinery, using 180°C geothermal fluid to generate 150°C process steam for biomass gasification and reforming. In one configuration, 105 kg·s⁻¹ of geothermal fluid produced 16 kg·s⁻¹ of steam, with excess heat converted to approximately 4.5 MW electricity via an Organic Rankine Cycle (ORC) at 43% efficiency [137]. A second configuration used flash separation to supply both process heat and power. Across scenarios, biomass-to-fuel energy efficiency reached approximately 39%, illustrating geothermal heat's role in reducing energy losses. Comparative studies indicate that coupling biomass syngas with internal combustion engines or gas turbines can increase electricity generation by up to 49% relative to conventional lignin combustion with geothermal support [138]. Notably, geothermal resource enthalpy primarily satisfies high-temperature demands (~200°C), with low-grade heat needs often met through internal waste heat recovery, underscoring its complementary function in integrated heat cascades. Geothermal integration is also proved effective in industrial clusters. Atkins et al. (2016) demonstrated that geothermal heat supplied to pulp and paper facilities can replace black liquor combustion, allowing up to 56% of black liquor to be gasified for syngas and downstream urea production [139]. In New Zealand, 78 MW of geothermal heat reduced biomass combustion while increasing syngas availability, lowering power generation losses from 15.23 MW to roughly 7.5 MW when paired with ORC technology. In Lausanne (Switzerland), a hybrid geothermal–biomass system has been studied for urban energy applications. The system utilizes excess geothermal heat to enhance biomass conversion, thereby improving process efficiency while reducing operational costs and environmental impacts. The system performs well under changing energy demand, including seasonal and hourly variations [140].

Case studies on gamma-valerolactone (GVL) production demonstrated that on-site wind turbines, integrated with biomass and hydrogen management, reduced GHG emissions by 92.5% compared to natural gas-based configurations [141]. Optimized designs required 1.85 MW of electricity from wind, alongside 3.99 MW of thermal power, while green hydrogen from electrolysis served both as a process reagent and an energy storage vector, enabling peak-shaving and valley-filling. In regions with high grid decarbonization, such as France, wind-powered biorefineries are competitive with biomass-fueled systems [142–145]. However, hydrogen production and storage introduce additional process hazards, accounting for roughly 10% of the total risk profile. The combination of geothermal and wind resources allows biorefineries to achieve both continuous thermal supply and flexible electrical support. Geothermal heat ensures steady operation of high-temperature processes such as gasification, steam reforming, and distillation, while wind-derived electricity supports electrolysis, pumping, and other electricity-intensive units. This synergistic integration maximizes the use of renewable energy, reduces fossil fuel dependence, and enables flexible valorization of lignocellulosic residues. In practice, geothermal wells in regions such as New Zealand's Central North

Island deliver 10–40 MW of thermal energy at 150°C–220°C, often coupled with ORC units for simultaneous process heat and low-carbon electricity generation. Wind energy further complements these resources by enabling electrified chemical production, energy storage through hydrogen, and improved peak-load management [136,137,140,141,146].

Table 5: Summary of research on geothermal and wind energy integration in biorefineries.

Feedstock/ Process	Renewable Input	Scale/Capacity	Energy Out- put/Efficiency	Main Findings	References
Lignocellulosic biomass	Geothermal heat (low- to medium-enthalpy, 150°C–220°C)	2000 t·day ^{−1} corn stover	Process steam 150°C; electricity ~4.5 MW (ORC); overall biomass-to-fuel efficiency ~39%	Geothermal heat reduces internal biomass combustion, preserves lignin for high-value applications, complements ORC power generation	[137]
General lignocellulosic DBR	Geothermal heat	Decentralized biorefinery	Increased lignin availability; improved electricity self-sufficiency	Geothermal supply allows diversion of lignin to chemicals and materials, enhancing resource efficiency	[136]
Pulp & paper residues	Geothermal heat	Industrial cluster, New Zealand	78 MWth thermal input; syngas availability increased; power losses reduced from 15.23 MW → 7.5 MW	Geothermal heat displaces black liquor combustion; enables higher syngas recovery and product diversification	[139]
Urban biomass + DBR	Geothermal heat	Urban-scale biorefinery	Reduced operational cost; enhanced biomass conversion efficiency	Geothermal heat supports seasonal and hourly thermal demands; improves process stability	[140]
Gamma-valerolactone (GVL)	Wind electricity; green H ₂	Pilot-scale electrified DBR	Electricity: 1.85 MW; thermal demand: 3.99 MW; GHG reduction: 92.5%	Wind-derived electricity with H ₂ enables peak-shaving, valley-filling, and process electrification	[141]
Hybrid geothermal + biomass	Geothermal + biomass	Central North Island, New Zealand	10–40 MW thermal; ORC electricity; continuous heat supply	Baseline geothermal heat ensures stable high-temp processes; ORC converts excess heat to electricity; frees biomass for higher-value products	[136,137]
Electrified biomass DBR	Wind electricity + H ₂ storage	Regional electrified DBR	Flexible electricity supply; supports electrolysis; enables low-carbon operations	Wind + H ₂ enhances electricity flexibility, peak-load management, and renewable integration	[141,144,145]

4.3 Polygeneration Biorefinery Systems

Lignocellulosic biomass represents a versatile feedstock for biorefineries, with the majority of its chemical energy stored in cellulose, hemicellulose, and lignin. Effective utilization of lignin-rich residues is critical to improving the overall energy recovery and economic performance of biorefineries. Research on circular bioenergy-integrated biorefinery systems is summarized in Table 6. Lignin can be combusted to supply process heat or valorized into high-value products such as biochar, bioplastics, or platform chemicals, thereby supporting both energy and material recovery objectives. For corn stover-based biorefineries, Nwai and Patel (2023) reported that energy recovery from ethanol production accounts for approximately 32% of feedstock HHV, with surplus electricity contributing 2.44% HHV. Integration of heat recovery and process optimization reduced thermal energy demand from 29.4 to 19.56 MJ·kg⁻¹ ethanol, while electricity supplied roughly 20% of total process energy [133]. Polygeneration strategies that combine solar, biomass, and biogas systems further enhance energy conversion efficiency, achieving up to 75% overall energy utilization [147].

Hybrid approaches that allow partial lignin combustion while exporting residues for co-products demonstrate both increased net energy output and improved process profitability, underscoring the importance of co-product valorization in biorefinery design [133]. Beyond ethanol production, biomass-powered combined heat and power (BCHP) systems integrated into district heating systems (DHS) exemplify the principles of circular bioenergy. When optimally sized and coordinated with thermal energy storage, BCHP–DHS systems can achieve overall efficiencies of 70%–90%, compared to 20%–35% electrical efficiency for stand-alone biomass power plants. Thermal energy storage, typically in the form of hot water tanks or phase-change materials, decouples heat production from demand, increases annual capacity factors by 10%–20%, and reduces peak-load operation of CHP units [148].

Integration of anaerobic digestion with thermochemical conversion processes has emerged as a particularly effective strategy for circular bioenergy systems. Deng et al. (2020) proposed a cascading system combining seaweed anaerobic digestion with forest residue pyrolysis, where pyrolysis biochar enhanced biomethane yields by 16%–17% and accelerated volatile fatty acid conversion. Combustion of syngas and surplus biochar satisfied the system's heat demand, while bio-oil yields increased by 10% and digestate mass was reduced by 26%, lowering land and transport requirements [149]. Similarly, Monlau et al. (2015) evaluated anaerobic digestion coupled with digestate pyrolysis, demonstrating that pyrolysis of dried digestate at 500°C produced 58.4 wt.% bio-oil, 32.8 wt.% char, and 8.8 wt.% syngas, with respective HHV/LHV of 23.5 MJ·kg⁻¹ and 15.7 MJ·Nm⁻³. Integration increased total electricity output to 14,066 kWh/day, a 42% improvement over stand-alone anaerobic digestion, while generating surplus heat sufficient for digestate drying, illustrating enhanced energy efficiency and sustainability [150].

Other studies have confirmed the value of hybrid thermochemical-biochemical systems. Righi et al. (2016) examined pyrolysis–anaerobic digestion (PYDA) of corn stover, reporting electricity outputs of 980–3200 MJ per functional unit, with additional 1640 MJ obtained via biochar combustion. Total non-renewable primary energy savings ranged from 11,000–14,000 MJ, with biochar soil amendment yielding greater greenhouse gas reductions than direct combustion [151]. Caiardi et al. (2022) compared single anaerobic digestion with integrated anaerobic digestion–pyrolysis (AD-PY) treating sewage sludge and quinoa residues, noting that while single AD achieved slightly superior performance in global warming potential and fossil energy savings, integrated systems offer greater potential for valorizing bio-oil and biochar [152]. Salman et al. (2017) similarly reported that AD–pyrolysis integration enhanced biomethane production by 20% and achieved overall system energy efficiency of 67%, compared to 52% for AD alone, with 0.6 MW of surplus heat available for internal demand or district heating [153]. Hybridization with advanced thermal pathways, such as hydrothermal carbonization coupled with AD (HTC-AD), also enables effective energy recovery from high-moisture biomass streams. Heidari et al. (2020) compared direct combustion

(DC) and HTC-AD of sawdust (10% moisture), showing that while DC slightly outperformed under low-moisture conditions, HTC-AD achieved superior efficiency at higher moisture contents due to improved fuel upgrading and biogas utilization. System performance was highly sensitive to biomass HHV, water-to-biomass ratio, acid-forming potential, and heat recovery strategies [154]. Municipal solid waste (MSW) represents a complementary feedstock for circular bioenergy systems, providing flexibility and resilience against feedstock variability. With projected global generation of 3.4 billion t·yr⁻¹ by 2050 and LHV values of 6–12 MJ·kg⁻¹, MSW can be co-gasified or co-pyrolyzed with lignocellulosic biomass to stabilize energy supply and reduce reliance on single feedstocks [155,156].

Table 6: Overview of research on circular bioenergy-integrated biorefinery systems.

System	Conversion Pathway	Major Outputs	Energy Efficiency/Recovery	Main Findings	References
Corn stover DBR	Ethanol production + heat integration	Ethanol, electricity	Ethanol energy recovery 32% HHV; electricity 2.44% HHV	Heat integration reduced thermal input from 29.4 to 19.56 MJ/kg; electricity ~20% of total energy	[133]
Solar + biomass + biogas DBR	Polygeneration	Ethanol, electricity	Overall energy conversion up to 75%	Hybrid polygeneration enhances energy efficiency and co-product valorization	[147]
BCHP + District Heating System	Combustion-based CHP	Heat, electricity	Overall efficiency 70%–90%	TES decouples heat generation, increases capacity factor 10%–20%; peak-load reduction	[148]
Seaweed AD + Forest residue pyrolysis	AD + Pyrolysis	Biomethane, bio-oil, biochar, heat	Biochar addition increased biomethane 16%–17%; bio-oil yield +10%	Digestate reduced 26%; internal heat supplied via syngas/biochar	[149]
Digestate pyrolysis + AD	AD + Pyrolysis	Bio-oil, biochar, syngas, electricity	Total electricity output 14,066 kWh/day; +42% vs. AD alone	Surplus heat sufficient for digestate drying; revenue 1168 €/day	[150]

(Continued)

Table 6 (continued)

System	Conversion Pathway	Major Outputs	Energy Efficiency/Recovery	Main Findings	References
Corn stover	PYDA: Pyrolysis + AD	Electricity, bio-oil, biochar	11,000–14,000 MJ non-renewable primary energy saved	Biochar combustion maximized energy recovery; soil amendment maximized GHG savings	[151]
Sewage sludge + quinoa residue	AD-Pyrolysis	Biogas, bio-oil, biochar	Environmental impacts comparable; fossil energy savings –6900 vs. –9900 MJ/t	Effective if pyrolysis products valorized; careful digestate management needed	[152]
Lignocellulosic waste	AD + Pyrolysis	Biomethane, electricity, heat	Energy efficiency 67% vs. 52% for AD alone; +20% biomethane	Pyrolysis products reformed and methanated; biochar stabilized digester	[153]
Sawdust (16 g/s, 10% moisture)	HTC-AD + Rankine/Brayton cycles	Electricity, heat	DC 101 kW vs. HTC-AD 95.79 kW (low moisture); HTC-AD better at higher moisture	Efficiency sensitive to water-to-biomass ratio, HHV, and heat recovery	[154]
Lignocellulosic biomass + MSW	Co-gasification/co-pyrolysis	Syngas, bio-oil, heat	LHV 6–12 MJ/kg (MSW contribution)	Enhances feedstock flexibility, stabilizes operation under fluctuating renewable supply	[155,157]

4.4 Solid Oxide Fuel Cell–Based Hybrid Biorefinery Systems

Solid oxide fuel cell (SOFC)–based hybrid biorefinery systems represent a promising route for high-efficiency electricity and CHP generation from biomass, particularly wet or high-moisture feedstocks.

Research on hybrid biorefinery systems incorporating solid oxide fuel cells is predominantly based on mathematical simulations, as summarized in [Table 7](#). By coupling biomass gasification with high-temperature electrochemical conversion in SOFCs, these systems achieve superior energy and exergy performance compared with standalone gasification or conventional power generation technologies. In addition, the integration of gas turbines (GT) or micro gas turbines (MGT) further enhances power output and system flexibility through bottoming cycles and efficient heat utilization. Facchinetti et al. (2012) evaluated an integrated hydrothermal gasification–SOFC–GT system for wet waste biomass. Through systematic optimization of heat and exergy recovery between the gasification stage (673–773 K) and SOFC operation, the configuration achieved a first-law electrical efficiency of 63%, exceeding a comparable non-integrated system by approximately 4 percentage points and prior literature values by 10%. Tight thermal integration allowed maximal SOFC fuel utilization and minimized exergy losses, demonstrating the potential of hydrothermal gasification coupled with SOFC–GT hybrids for wet biomass [\[158\]](#). Similarly, Toonssen et al. (2010) assessed multiple gasification pathways methane-rich, hydrogen–methane, and hydrogen-rich integrated with SOFC–GT systems. Across all pathways, electrical exergy efficiencies reached ~50%, highlighting the feasibility of high-efficiency conversion without energy-intensive drying, with system performance highly dependent on effective liquid–gas separation in the gasifier [\[159,160\]](#). Integration of energy storage further enhances flexibility. Diyoke and Wu (2020) analyzed a hybrid A-CAES–biomass gasification system providing 1.3 MW peak electricity and domestic heat. Total energy and exergy efficiencies were 38% and 29%, respectively, with electrical efficiency of 30% and effective electrical efficiency of 34%. Exergy losses were highest in the gasifier and dual-fuel engine, whereas compressors and expanders achieved 86%–89% exergy efficiency. While not meeting EU high-efficiency CHP criteria, the study demonstrated effective utilization of wet biomass with integrated storage, enabling self-drying and peak-shaving capabilities [\[161\]](#).

Large-scale hybrid systems integrating advanced thermal sources have also been explored. Nam et al. (2019, 2020) proposed fusion–biomass hybrid concepts, where high-temperature heat (>600°C–900°C) from a dual-coolant lithium–lead (DCLL) blanket supplies biomass gasification. Systems processing tens of thousands of tons per day of waste biomass achieved fuel output efficiencies of 35%–39% for diesel or hydrogen production, with net electricity output of 289 MWe and overall efficiency of 30% [\[162,163\]](#). These configurations highlight the potential of hybridizing external high-grade heat sources with biomass conversion to achieve baseload, low-carbon power and fuels at scale. Thermodynamic analyses emphasize the importance of reactor and gasification conditions for system performance. Athanasiou et al. (2007) demonstrated that high-temperature SOFC integration allows autothermal operation of gasifier–SOFC systems, yielding total electrical efficiencies of 43.3% when combining SOFC electricity and steam turbine recovery [\[164\]](#). Jia et al., (2015) and Sucipta et al. (2007) reported that steam-blown biomass gasification produces hydrogen-rich syngas, improving SOFC and hybrid system efficiencies (~40% electrical, 36% exergy CHP) compared with air or oxygen-blown systems. Gasifier design, steam-to-fuel ratios, and feedstock moisture strongly influence performance, emphasizing the need for precise operational control [\[165,166\]](#).

SOFC–MGT or SOFC–GT hybridization further enhances energy conversion. Fryda et al. (2008) reported that a combined SOFC–MGT system achieved the highest exergy electrical efficiency (35.6%) for small-scale CHP, with optimization of fuel utilization and biomass moisture levels [\[167\]](#). Bang-Møller et al. (2011) identified heat exchanger and gasifier losses as key exergy destruction points, showing that adding product gas preheating and optimized heat recovery networks could increase net electrical efficiency from 55.0% to 58.2% and overall cogeneration efficiency from 82.6% to 87.5% [\[168\]](#). Jia et al. (2021) extended this approach to integrated combined cooling, heating and power (CCHP) systems, combining downdraft gasifiers, SOFC, MGT, and absorption chillers. Optimized air flow and low biomass moisture (<20%) enabled electrical efficiency of 52%, exergy efficiency of 47%, and overall CCHP efficiency of 70%, with enhanced

heating and cooling output via exhaust gas management [169]. Multi-objective optimization studies further underscore the flexibility of SOFC-based hybrids. Borji et al. (2015) demonstrated that adjusting air-to-steam ratios, equivalence ratios, and SOFC operational parameters can maximize syngas LHV, electric efficiency (up to 39.1%), and total CHP efficiency ($\approx 60\%$) for small-scale biomass gasifiers coupled with planar SOFC and micro gas turbines. Jia et al. (2018) highlighted the importance of co-gasification feedstock composition (woody biomass vs. animal manure) and moisture control in achieving electrical efficiencies above 45% while minimizing capital costs associated with SOFC deployment [170].

Table 7: Summary of studies on solid oxide fuel cell–based hybrid biorefinery systems.

Feedstock	System Configuration	Scale/Capacity	Electrical Efficiency	CHP/CCHP Efficiency	Main Findings	References
Wet waste biomass	Hydrothermal gasification + SOFC + Gas Turbine	Pilot	63%	–	Optimized heat and exergy integration; 4 pp higher than non-integrated system; maximized SOFC fuel utilization	[158]
Wet biomass	Hydrothermal gasification + SOFC–GT	Pilot	$\sim 50\%$ (exergy)	–	Multiple gasification pathways tested; high efficiency without drying; sensitive to liquid–gas separation	[160]
Biomass	Biomass gasification + A-CAES	1.3 MW	30%	38% (energy), 29% (exergy)	Provides electricity and heat; effective wet biomass utilization; self-drying; peak-shaving capability	[161]
Waste biomass + fusion heat	Biomass gasification + SOFC + GT	63,700 t/day biomass; 364 MW fusion	30%–39%	–	Large-scale low-carbon fuel production; high-temperature heat enhances efficiency; moderate EROI (3.9)	[162,163]
Biomass	Gasifier + SOFC + Steam turbine	–	26.7% SOFC; total 43.3%	–	Autothermal operation; hydrogen utilization enhances performance	[164]

(Continued)

Table 7 (continued)

Feedstock	System Configuration	Scale/Capacity	Electrical Efficiency	CHP/CCHP Efficiency	Main Findings	References
Biomass	Gasifier + SOFC (air/steam/O ₂ -enriched)	–	28%–40%	36% (steam)	Steam gasification yields richer syngas; highest electrical and exergy efficiencies	[166]
Wet biomass	SOFC + Micro Gas Turbine	Small-scale	152–165 kW (SOFC), 79–118 kW (MGT)	–	Fuel composition and steam content critical; steam-blown feedstock improves efficiency	[165]
Biomass	Gasifier + SOFC/MGT/ SOFC–MGT	200 kg/h biomass	35.6% (exergy)	–	SOFC–MGT hybrid outperforms individual units; moisture optimization important	[167]
Two-stage biomass	Gasifier + SOFC + MGT	–	55%–58%	82%–87%	Heat exchanger optimization improves efficiency; exhaust heat utilized for biomass drying	[168]
Biomass	Downdraft gasifier + SOFC + MGT + absorption chiller	–	52%	70% (overall CCHP)	Gasifier air flow and low moisture critical; exhaust heat enhances cooling and heating	[169]
Biomass	Two-stage autothermal gasifier + planar SOFC + MGT	293 kW	39.1%	60%	Parametric and Pareto optimization; trade-offs between electric and CHP efficiency	[171]

(Continued)

Table 7 (continued)

Feedstock	System Configuration	Scale/Capacity	Electrical Efficiency	CHP/CCHP Efficiency	Main Findings	References
Woody biomass + animal manure	Co-gasification + SOFC + MGT	–	>45%	–	High woody fraction and low moisture optimize electrical efficiency; feedstock composition affects SOFC cost	[170]

Note: pp = percentage points; CHP = Combined Heat and Power; CCHP = Cooling, Heat, and Power; Exergy efficiencies reported where available; energy efficiency otherwise; All efficiencies are first-law unless otherwise stated (i.e., exergy efficiencies).

5 Comparative Perspective, and System-Level Implications

The evolution of biorefineries increasingly emphasizes system-level integration, leveraging renewable energy sources, industrial symbiosis, and co-product valorization to enhance efficiency, resilience, and environmental performance (Fig. 2). Beyond direct substitution of fossil heat or electricity, biorefineries can benefit from the strategic sharing of energy, material, and waste streams across co-located facilities. Examples include the integration of lignocellulosic biorefineries with municipal solid waste processing, anaerobic digestion, or microalgae cultivation for CO₂ utilization. Such configurations have demonstrated energy savings of up to 35%, water reductions of approximately 50%, and greenhouse gas (GHG) emission reductions of around 20%, highlighting the benefits of system-level optimization over isolated process improvements [172].

Cross-cutting insights from the literature reveal that renewable-integrated biorefineries can effectively extend the utility of chemical energy storage, improve renewable dispatchability, and reduce grid dependence. For instance, biocrude intermediates produced via thermochemical conversion act as long-duration energy storage, bridging temporal gaps in intermittent renewable generation. Hybrid solar–biomass systems have demonstrated the ability to supply fully renewable electricity while moderating reliance on the grid, with optimal biomass throughput largely dictated by the shape of the demand profile rather than peak loads alone [27,29]. Solar-assisted HTL and fast pyrolysis are complementary. HTL is advantageous for wet waste streams, whereas pyrolysis is better suited to dry lignocellulosic residues, offering pathways for feedstock-specific optimization [28,132,173].

Empirical and modeling studies confirm that hybrid renewable integration combining solar, geothermal, wind, and biomass enhances overall energy conversion efficiency, reduces GHG emissions, and enables high-value co-product generation, including lignin, biochar, and hydrogen. Geographically diverse case studies underscore this potential. For example, concentrated solar thermal–biomass hybrids in Australia, geothermal-assisted biorefineries in New Zealand, and wind-powered gamma valerolactone (GVL) production facilities in France demonstrate site-specific techno-economic advantages, with operational efficiency and environmental performance strongly influenced by local renewable resource availability, grid carbon intensity, and energy pricing [122,137,141].

Co-product valorization emerges as a critical determinant of both economic viability and resource efficiency. By substituting renewable heat or electricity for internal biomass combustion, lignin-rich residues

and other by-products can be redirected toward chemicals, materials, or secondary electricity generation, rather than being consumed for process heat. This strategy enhances net energy output and profitability, particularly when integrated with district heating systems or urban energy networks [136,139]. Operational safety, particularly in systems involving hydrogen production, high-temperature solar input, or geothermal heat, remains a central consideration for industrial deployment, influencing both design and regulatory compliance [141].

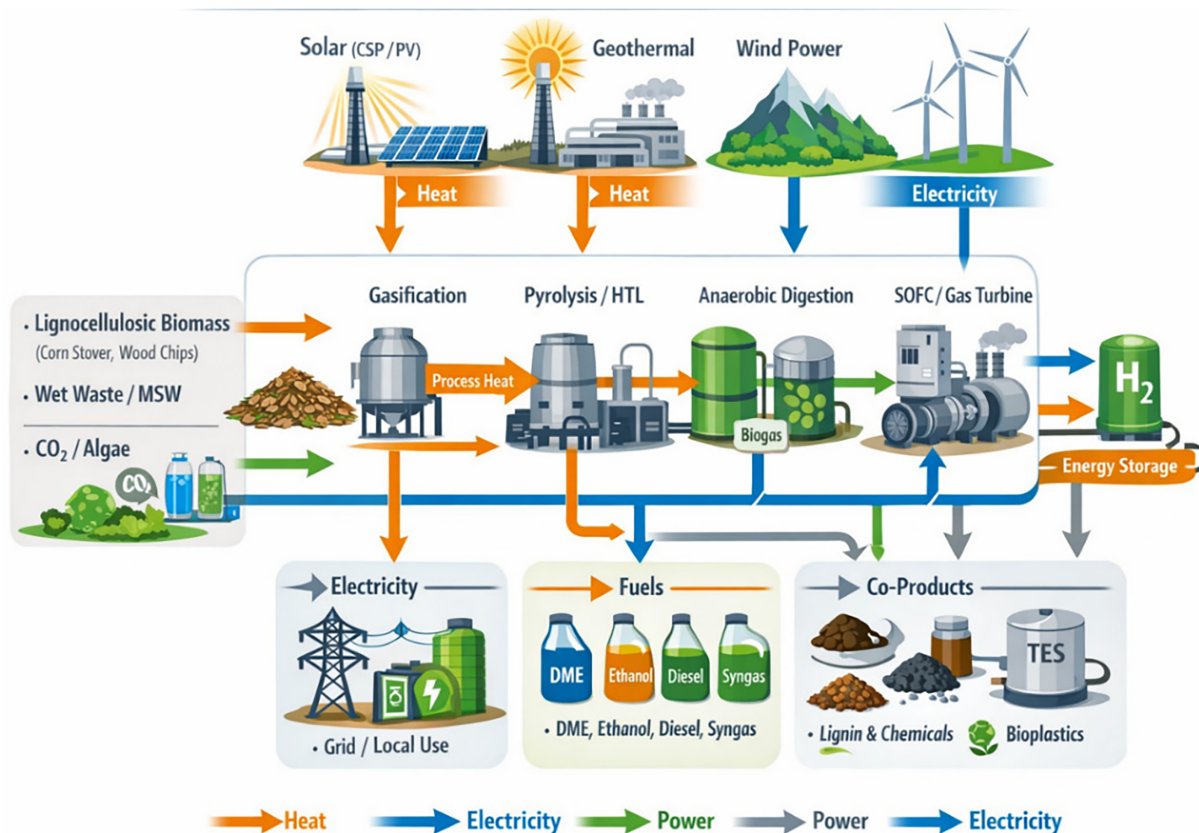


Figure 2: System level integration of renewable energy into hybrid biorefineries.

System-level analyses further highlight the complementary roles of solar energy and thermochemical conversion. High-temperature solar inputs, including concentrated solar power, synergize with gasification, fast pyrolysis, and HTL to increase energy self-sufficiency and product yield. Biochemical processes benefit more from low-temperature solar heat and renewable electricity, particularly when integrated with co-product valorization. Multi-output solar-biomass systems producing electricity, fuels, and chemicals have demonstrated improvements of up to 2.5% in energy efficiency, 3.4% in exergy efficiency, and reductions of nearly 40% in environmental impact, illustrating the value of holistic system design and cross-process integration [147].

Distributed solar-driven biorefineries offer modular and scalable solutions that reduce logistics energy requirements by 10%–30%, minimize operational risks associated with high-pressure or high-temperature processes, and facilitate flexible energy management. Coupled with complementary renewables such as geothermal and wind, these configurations provide robust, low-carbon platforms for biofuel and biochemical production. By combining renewable integration, co-product valorization, and modular deployment, hybrid

biorefineries present a near-term, scalable pathway toward resilient, resource-efficient, and environmentally sustainable biorefinery operations, capable of bridging intermittency challenges and supporting regional energy security.

6 Research Challenges and Future Directions to Biorefinery Autonomy

The transition toward fully autonomous biorefineries facilities capable of meeting their own energy demands using on-site renewable resources represents an important step toward a circular carbon economy. By integrating multiple renewable energy sources such as solar, wind, geothermal, biomass, and solid oxide fuel cells, these systems aim to operate independently of fossil-based grids. However, achieving this involves a complex interplay of technical, economic, environmental, and social challenges.

6.1 Technical Challenges

Biorefineries depend on a continuous and stable supply of heat and power to sustain their chemical and biological processes. However, renewable sources like solar and wind are inherently variable, with output fluctuating based on weather conditions. This intermittency can disrupt internal operations and compromise system reliability. When a high share of variable renewable energy is integrated into a facility-scale microgrid, issues such as voltage fluctuations, reverse power flows, and power quality disturbances may arise [174]. These challenges highlight the need for advanced solutions, including real-time energy forecasting, grid-forming inverters, and reactive power control systems, to ensure stable and reliable operation [175].

To overcome intermittency, baseload energy sources such as geothermal energy and SOFCs can play a critical role. Geothermal energy provides a stable and continuous heat supply, but its application is often limited by geographic availability and limited operational flexibility [176]. SOFCs, on the other hand, offer high-efficiency conversion of biomass-derived syngas into electricity. Despite their advantages, their integration remains challenging due to high operating temperatures, slow startup times, and sensitivity to thermal cycling [177]. Additionally, when fueled by biomass-derived syngas, SOFCs require stringent gas cleaning to prevent catalyst degradation, further complicating system design [178].

Autonomous biorefineries are inherently polygeneration systems, producing multiple outputs such as fuels, chemicals, heat, and power. While this improves overall efficiency, it also increases system complexity [179]. Maintaining stable operation becomes particularly challenging due to variations in biomass feedstock properties, such as moisture content and composition, which can change seasonally [180]. Integrating processes like biomass gasification with combined cycle systems requires careful control strategies to ensure consistent performance under these dynamic conditions [180].

6.2 Economic, Environmental and Social Challenges

Developing an autonomous biorefinery requires substantial upfront investment. In addition to core processing units, facilities must incorporate renewable energy generation systems, energy storage technologies, and microgrid infrastructure. Technologies such as SOFCs remain expensive due to material and manufacturing costs [177]. Moreover, the complexity of integrated polygeneration systems often results in long payback periods, making them less attractive to investors [180]. The added costs of system integration and operational control further increase financial risk.

Beyond the cost of energy generation, integrating renewable energy into biorefineries introduces additional system-level challenges and expenses. These include the need for internal grid upgrades, energy balancing mechanisms, and backup systems to ensure continuous and stable operation [175]. Such integration-related costs are often overlooked but can significantly increase the overall cost of operating

renewable-powered biorefineries, especially at higher levels of renewable penetration. Another important challenge arises from the spatial mismatch between renewable energy availability and the location of biorefinery processes. For example, optimal sites for solar or wind generation may not align with existing biorefinery infrastructure, requiring additional investment in energy transport, storage, or transmission systems. This not only increases costs but also introduces practical challenges related to land use, infrastructure development, and regulatory approvals.

Existing energy markets are not well designed to support industrial energy autonomy. Facilities that generate their own energy and reduce grid dependency often receive limited financial incentives. There are currently no clear regulatory frameworks for businesses that both produce and consume their own energy. As a result, many companies find it too risky and are holding off on making the transition [181]. Without policies that reward flexibility, resilience, and reduced emissions, the transition toward autonomous biorefineries remains economically challenging.

Achieving full energy autonomy requires significant land resources, particularly for solar and wind installations. This can lead to competition with agriculture or ecological conservation, especially in densely populated regions. While autonomous biorefineries reduce operational emissions, it is also important to consider the lifecycle impacts of renewable technologies, including the production and disposal of solar panels, wind turbines, and batteries. Geothermal systems may also raise concerns related to groundwater use and induced seismicity [182].

Large-scale integrated facilities often face resistance from local communities. This has been due to concerns related to land use, visual impact, and noise. Gaining public acceptance requires transparent communication, inclusive planning, and fair distribution of economic and social benefits [182].

6.3 Policy and Regulatory Aspects

The successful commercialization of renewable-powered biorefineries relies not only on technological advancements but also on robust and supportive policy frameworks. Government incentives, carbon pricing instruments, renewable energy mandates, and sustainable biofuel regulations play a pivotal role in determining economic viability, attracting investment, and enhancing market competitiveness [183]. Within the EU, the revised Renewable Energy Directive (RED III, Directive (EU) 2023/2413) sets more ambitious renewable energy targets while introducing mandatory quotas for renewable fuels of non-biological origin in the industrial and transport sectors. In addition, RED III reinforces sustainability and GHG emission reduction criteria for biomass-based fuels and renewable hydrogen, thereby improving regulatory certainty and fostering long-term investment in low-carbon technologies [184].

Moreover, policy instruments such as the EU Emissions Trading System, carbon pricing mechanisms, renewable hydrogen certification, and sustainability verification schemes enhance the competitiveness of renewable fuels by accounting for the environmental costs associated with fossil fuel consumption [185]. Certification systems for biomass feedstocks and renewable hydrogen are equally important to ensure feedstock traceability, verify lifecycle GHG emission reductions, and demonstrate compliance with sustainability standards [185,186].

6.4 Future Research Directions

Advanced Hybrid Energy Integration: Future research should focus on improving how multiple renewable energy sources are combined within biorefinery systems. For example, hybrid systems combining geothermal and solar energy have shown strong potential, with nearly 45% of geothermal hybrid applications incorporating solar integration [176]. However, there is still a need to better understand optimal

system design, including sizing, integration strategies, and control approaches. Developing standardized frameworks for designing and evaluating hybrid systems will help accelerate their practical deployment in biorefineries.

Optimization of Geothermal Integration: Geothermal energy can provide a reliable and continuous heat source for biorefineries, but its full potential remains underutilized. Research should focus on expanding its applicability through enhanced geothermal systems and improving its integration with other renewables such as solar. Low-temperature geothermal applications for process heating and district energy systems also deserve attention. Coupling geothermal systems with energy storage can further improve operational flexibility [176].

Energy Storage Development: Energy storage is central to balancing the intermittent nature of renewable energy in biorefineries. Future research should focus on improving storage technologies in terms of efficiency, cost, and durability. This includes advancements in high-performance batteries, thermal energy storage systems for process heat, and Power-to-X pathways that convert excess energy into hydrogen or synthetic fuels. Hybrid storage systems that combine different technologies may offer a practical solution by leveraging their complementary strengths [175].

Advancements in Solid Oxide Fuel Cells: Solid oxide fuel cells offer a promising pathway for converting biomass-derived syngas into electricity with high efficiency. However, further research is needed to enhance their practicality in biorefinery environments. Key priorities include reducing operating temperatures to improve durability, developing more stable materials, and improving resistance to degradation. In addition, better integration strategies such as coupling SOFCs with carbon capture systems or hybrid gas turbine cycles could significantly improve overall system performance [177,178].

Next-Generation Biomass Conversion Technologies: Advancing biomass conversion processes remains essential for efficient biorefinery operation. Future work should focus on developing flexible pretreatment methods capable of handling diverse and variable feedstocks. Integrated biorefinery concepts that enable the simultaneous production of fuels, chemicals, heat, and power should be further explored. Process intensification and modular system designs can help reduce costs and improve scalability. Additionally, combining biomass conversion with carbon capture technologies offers a pathway toward negative emissions [179,180].

Smart Energy Systems and Digitalization: Digital technologies are expected to play a key role in enabling autonomous and flexible biorefineries. Tools such as artificial intelligence, machine learning, and advanced control systems can improve energy management by predicting renewable energy availability and adjusting operations accordingly. The development of smart microgrids, real-time monitoring systems, and intelligent energy management platforms will be essential for maintaining stable operation under variable renewable energy inputs [175].

Policy and Market Support: The transition toward renewable-powered biorefineries will require supportive policy and market frameworks. Despite some policy developments by IEA and EU, regulatory fragmentation, lengthy permitting procedures, and uncertainty surrounding future policy implementation continue to impede the widespread deployment of decentralized biorefineries. Therefore, harmonized regulations, stable long-term financial incentives, simplified permitting processes, and consistent carbon pricing policies are essential to encourage private investment and accelerate the transition toward a circular, low-carbon, and climate-neutral bioeconomy [183,184]. In addition, future research should explore mechanisms that reward energy flexibility, autonomy, and low emissions. This includes dynamic pricing models, improved market structures for ancillary services, and policies that support distributed energy systems and industrial energy producers. Clear regulatory pathways will be essential to reduce uncertainty and encourage investment.

Circular Economy and Sustainability: Finally, integrating circular economy principles into biorefinery systems is critical for long-term sustainability. This includes designing renewable energy technologies with recyclability in mind, improving material recovery processes, and minimizing environmental impacts across the entire lifecycle. Future research should also address sustainable sourcing of critical materials and develop more comprehensive assessment methods that account for environmental and social impacts.

7 Conclusions

Renewable energy-integrated autonomous biorefineries offer a promising pathway toward a more sustainable and circular carbon economy. By combining biomass conversion with locally available solar, wind, and geothermal resources, these systems can significantly improve energy efficiency while reducing greenhouse gas emissions. Their decentralized nature not only lowers the need for biomass transportation but also strengthens local energy security and enables better use of municipal and agricultural waste streams. In addition, the co-production of value-added products such as green hydrogen, bio-oil, and biochar enhances both resource efficiency and economic viability. Despite these advantages, several challenges remain. Intermittency of renewable energy, high capital investment, feedstock variability, and durability of catalysts and reactors continue to limit large-scale deployment. Environmental concerns and gaps in techno-economic and life-cycle assessments further complicate implementation. Moreover, the success of such systems often depends on supportive policy frameworks and market incentives. Moving forward, research should focus on integrated system optimization, pilot-scale validation, and location-specific designs that balance technical, economic, and environmental goals. The development of modular and flexible biorefineries will be key to overcoming these barriers. Ultimately, autonomous biorefineries have the potential to play a vital role in meeting future energy demands while advancing global sustainability objectives.

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Nomenclature

Abbreviations: The following abbreviations are used in this manuscript.

Abbreviation	Meaning
A-CAES	Adiabatic Compressed Air Energy Storage
AD	Anaerobic Digestion
AD-PY	Anaerobic Digestion–Pyrolysis

BCHP	Biomass Combined Heat and Power
CCHP	Combined Cooling, Heating, and Power
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CO ₂	Carbon Dioxide
CSP	Concentrated Solar Power
DBR	Design Basis Report/Biorefinery configuration
DC	Direct Combustion
DCLL	Dual-coolant lithium–lead
DHS	District Heating System
EC	European Commission
EROI	Energy Return on Investment
EU	European Union
GHG	Greenhouse Gas
GT	Gas Turbine
GVL	Gamma Valerolactone
HHV	Higher Heating Value
HRES	Hybrid Renewable Energy Systems
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
LHV	Lower Heating Value
MGT	Micro Gas Turbine
MSW	Municipal Solid Waste
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
PYDA	Pyrolysis–Anaerobic Digestion
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
WGS	Water Gas Shift

Symbols: The following symbols are used in this manuscript.

Symbol	Meaning	Unit
c_p	Specific heat capacity	$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
C (solids)	Solids concentration	kg
d_f	Feed particle size	μm
d_p	Product particle size	μm
E	Energy	MJ or kJ
E_g	Grinding energy	$\text{kJ}\cdot\text{kg}^{-1}$
Ex	Exergy	MJ or kJ
Ex_Q	Exergy of heat	MJ or kJ
k_B	Bond's work index	$\text{kJ}\cdot\text{kg}^{-1}$
m	Mass	kg
$\dot{m}$	Mass flow rate	$\text{kg}\cdot\text{s}^{-1}$
m_b	Biomass mass	kg
m_{vap}	Mass of vaporized fluid	kg

Symbol	Meaning	Unit
m_w	Mass of water removed	kg
MC	Moisture content	kg
P	Pressure	Pa or bar
P_1	Initial pressure	Pa or bar
P_2	Final pressure	Pa or bar
Q	Heat energy	MJ or kJ
Q_{AD}	Heat requirement (anaerobic digestion)	MJ
Q_{dry}	Heat required for drying	MJ
Q_{fast}	Heat required for fast pyrolysis	MJ
Q_{gas}	Heat required for gasification	MJ
$Q_{heat-up}$	Heat required for temperature rise	MJ
Q_{loss}	Heat loss to surroundings	MJ
Q_{min}	Minimum heat for evaporation	MJ
Q_{net}	Net external heat requirement	MJ
Q_{rxn}	Heat of reaction	MJ
$Q_{sensible}$	Sensible heat	MJ
Q_{slow}	Heat required for slow pyrolysis	MJ
Q_{tor}	Heat required for torrefaction	MJ
R	Universal gas constant	J·mol ⁻¹ ·K ⁻¹
T	Absolute temperature	K
T_0	Ambient/reference temperature	K
T_{op}	Operating temperature	K
V	Volumetric flow rate	m ³ ·s ⁻¹
W	Work	MJ or kJ
W_{comp}	Compression work	kJ·mol ⁻¹
W_{pump}	Pumping work	MJ or kJ
X	Moisture content (mass fraction)	kg
$Y_{product}$	Product yield	L·kg ⁻¹
ΔH	Enthalpy change	kJ·mol ⁻¹ or kJ·kg ⁻¹
ΔH_{AD}	Enthalpy (anaerobic digestion)	kJ·mol ⁻¹
ΔH_{char}	Enthalpy (char formation)	kJ·mol ⁻¹
ΔH_{ferm}	Enthalpy (fermentation)	kJ·mol ⁻¹
ΔH_{hemi}	Enthalpy (hemicellulose decomposition)	kJ·mol ⁻¹
ΔH_{rxn}	Heat of reaction	kJ·mol ⁻¹
ΔH_{vap}	Latent heat of vaporization	kJ·kg ⁻¹
ΔP	Pressure difference	Pa
ΔT	Temperature change	K
η	Efficiency	–
ρ (slurry)	Slurry density	kg·m ⁻³

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