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A Comprehensive Exploration of Biomass Gasification Technologies Advancing United Nations Sustainable Development Goals: Part II

Reactor types, power generation, current status and future challenges

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Part II of this review focuses on methodologies and protocols employed in biomass gasification, recognising its pivotal role in sustainable energy generation. Additionally, the article discusses the challenges associated with gasification technology, such as tar formation, biomass heterogeneity and uneven biomass supply in different seasons. It emphasises the need for further research and infrastructure development to overcome these barriers and facilitate the efficient distribution and commercialisation of biomass gasification technology. Overall, the scope of the article extends to providing insights into the status, challenges and future prospects of biomass gasification for achieving sustainable energy goals.

Keywords

renewable energy, greenhouse gas, biomass, gasification, sustainability

This work follows from Part I (1).

1. Reactors Employed in the Gasification Process

The gasification process is significantly influenced by the choice of reactor and, thus, the design of the reactor directly affects the quality of the producing gas. Various gasifying reactors have been created, including fixed bed gasifiers, moving bed gasifiers, fluidised bed gasifiers and entrained flow gasifiers. Fixed bed gasification encompasses updraft, downdraft and horizontal draft. The types of gasifiers that utilise fluidised beds are bubbling fluidised bed, fluidised beds and double fluidised bed. The gasifiers can be categorised into different types as illustrated in **Figure 1**. The gasification process hinges greatly upon the selection and design of the reactor, as this choice profoundly impacts the quality of the resultant gas.

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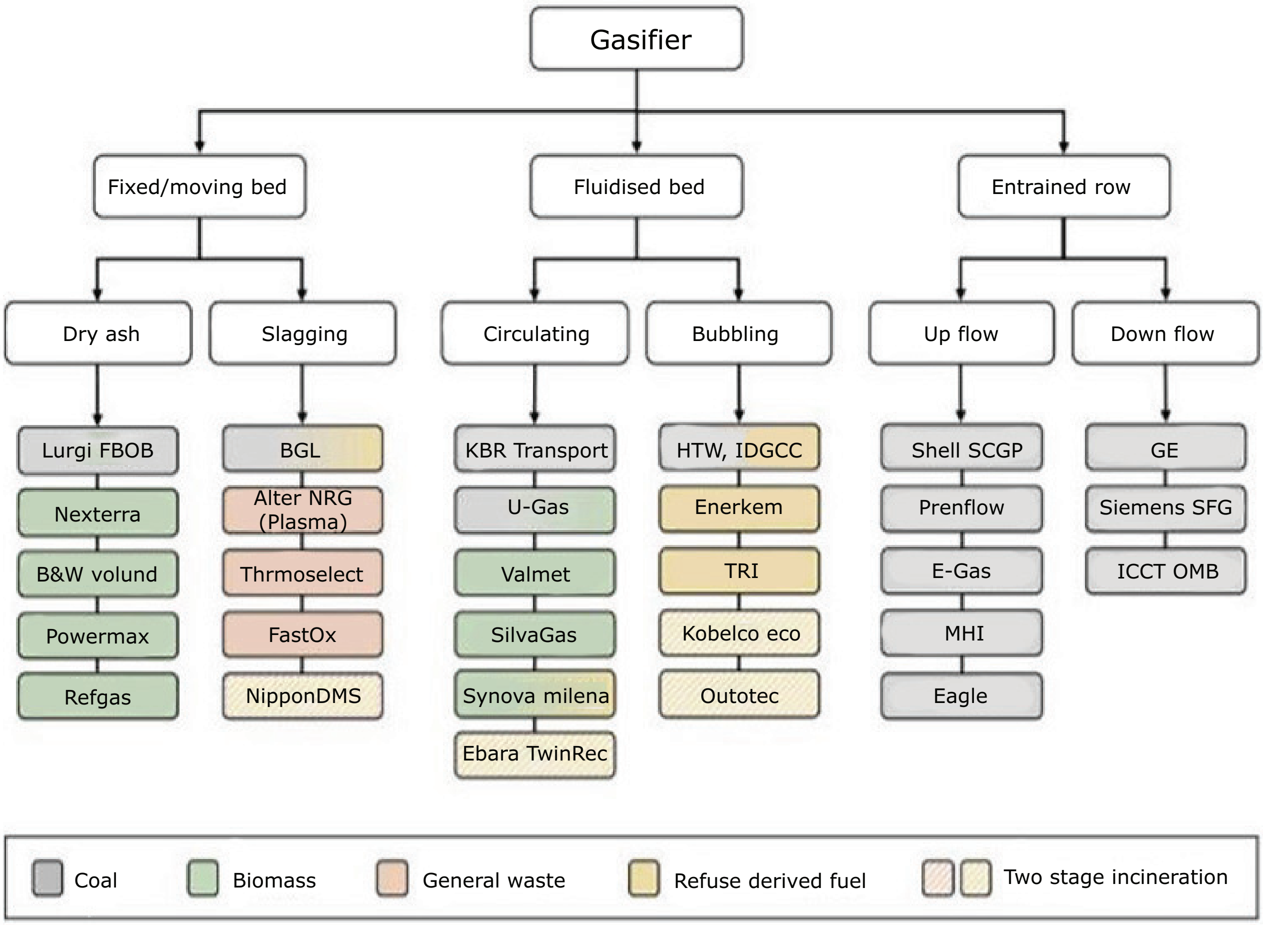

Fig. 1. Classification by feedstock type of gasifiers and commercially available technologies. Reprinted from (2) under Creative Commons license 4.0 (CC BY 4.0)

Fixed bed gasification represents a category of reactors that includes updraft, downdraft and horizontal draft configurations. These reactors operate by feeding the biomass feedstock and allowing it to move through a stationary bed of inert material. Updraft gasifiers feature a counter-current flow of biomass and gas, promoting thorough combustion and efficient gasification. In contrast, downdraft gasifiers introduce the biomass at the top, with gas and heat traveling downward through the bed, ensuring better tar conversion and gas quality. Horizontal draft gasifiers, meanwhile, facilitate a crossflow of gases and biomass, offering versatility in feedstock compatibility and gasification efficiency.

Fluidised bed gasifiers constitute another class of reactors, employing a bed of granular material that is fluidised by an upward flow of gas. This dynamic fluidisation enhances heat transfer and mass transfer, resulting in rapid and efficient gasification. Within this category, bubbling fluidised bed and circulating fluidised bed gasifiers are prominent variants, each distinguished by the velocity and behaviour of the fluidising gas and biomass particles. Additionally, double fluidised bed gasifiers utilise two fluidised beds interconnected by a gas transfer system, enabling enhanced tar cracking and syngas quality through staged gasification and catalytic conversion.

In summary, the selection of a gasification reactor is a critical consideration in optimising the gasification process for biomass conversion. By understanding the principles and operational characteristics of fixed bed, fluidised bed and entrained flow gasifiers, researchers and engineers can tailor gasification systems to meet specific requirements for syngas production and energy generation. A method of coal gasification that represents both the versatility of gasification feedstock and the vast range of products and application of gasification technology has been demonstrated (3).

1.1 Fixed Bed Gasifier

Fixed bed gasifiers are considered the optimal solution for smaller power production plants with a capacity of 10 MW (4). They are categorised as gasifiers for updraft and downdraft (5–7). In the former scenario, biomass is supplied from the upper part while gasifying agent (GA) is supplied from the lower part in a counter-current manner (8–10). The biomass and gasification agent are introduced from the top in a co-current manner, as shown in Figure 4 in Part I (1). **Figure 2** illustrates the operational concept of updraft and downdraft gasifiers (11). The biomass undergoes a series of steps, including drying and pyrolysis, in updraft reactors (12). Eventually, the resulting syngas is sucked from the top and reaches the combustion zone.

Conversely, downdraft gasifiers operate with both biomass and GA introduced from the top, where they undergo pyrolysis and combustion within the drying zone. This process results in syngas formation at the bottom of the reactor (13). In downdraft configurations, gaseous byproducts from pyrolysis are directed to the reduction region, while in updraft configurations, they are immediately incorporated into the syngas stream.

1.2 Fluidised Bed Gasifier

Fluidised bed gasifiers are commonly used for large-scale facilities due to their ease of scalability (14, 15). The gasifiers are categorised as fluidised bubbling bed gasifiers and dual bed gasifiers with distinct chambers (16). Both utilise the fluidisation idea of a solid bed. The GA serves as a fluidisation agent in bubbling fluidised bed systems, with a fluidisation speed of 2–3 m^{-2}. It is introduced from the bottom of the bed, allowing for gasification to take place within the bed itself (**Figure 1**). The process of gasification takes place in a dual-bed gasifier in two distinct stages (17, 18). The process of combustion occurs initially within the combustion chamber, where the necessary heat is produced for gasification. Subsequently, under the influence of a swift gas flow (5–10 m s^{-1}) within the fluidised bed gasifier, the processes of pyrolysis and gasification take place. The syngas is separated from the bed material by a cyclone separator located at the reactor outflow (19, 20) (**Figure 3**). The fluidised bed gasifier exhibits efficient transport of both mass and heat, resulting in consistent temperatures within the gasifier. Moreover, it can accommodate various types of biomass feedstock. Catalysts might be employed within the gasifier bed to enhance the elimination of tar (15, 21–24). The temperature range for operating a bubbling fluidised bed gasifier is between 700°C and 900°C. The syngas composition consists of 30–60 vol% hydrogen, 10–25 vol% carbon monoxide, 15–20 vol% CO_2 and 8–12 vol% methane. On the other hand, the circulating fluidised bed gasifiers operate at a temperature range of 700°C to 900°C. The syngas composition for these gasifiers is

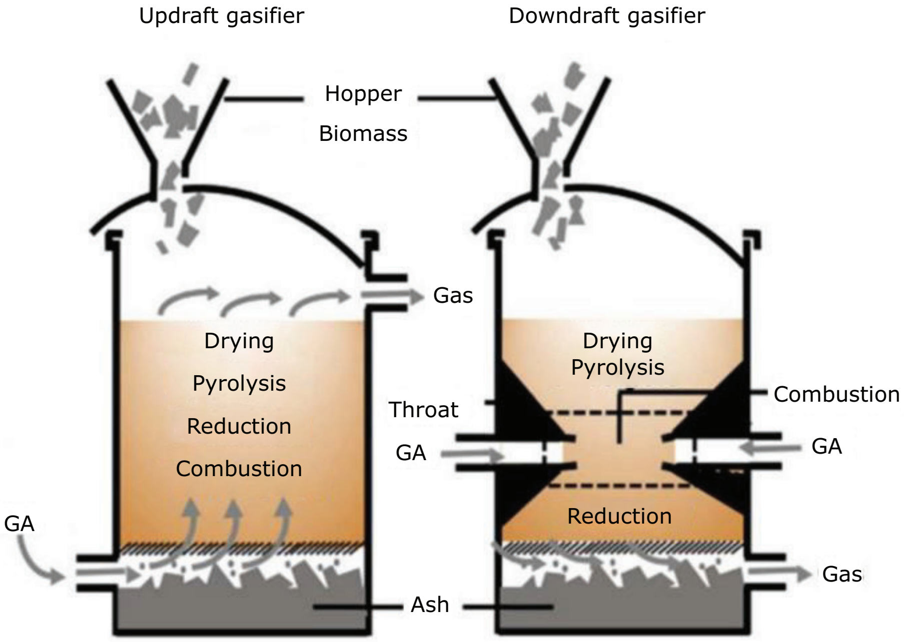

Fig. 2. Fixed bed gasifier schematisation. Reprinted from (2) under Creative Commons license 4.0 (CC BY 4.0)

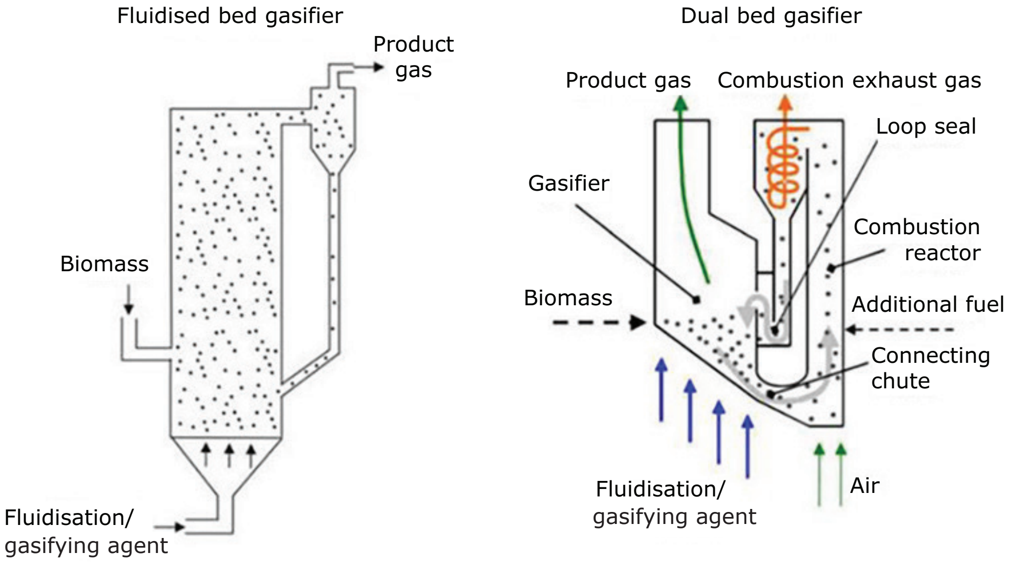

Fig. 3. Fluidised bed gasifier schematisation. Reprinted from (2) under Creative Commons license 4.0 (CC BY 4.0)

22–27 vol% hydrogen, 27–40 vol% carbon monoxide, 39–42 vol% CO_2 and 7–9 vol% methane (25).

Spouted beds and fountain confined spouted beds are innovative variations of fluidised bed reactors that have garnered interest for their potential applications in biomass gasification processes. These reactors offer distinct advantages and challenges, each influencing their suitability for biomass gasification. Spouted beds are characterised by a central jet of gas that induces a vigorous circulation of solids within the bed, creating a 'spout' or column of solids along the reactor axis. This intense mixing enhances heat and mass transfer rates, making spouted beds attractive for high-temperature processes like gasification. In biomass gasification, spouted beds offer efficient tar cracking and gas-solid interactions, leading to improved syngas quality. However, maintaining stable operation and preventing particle elutriation can be challenging in spouted beds, especially with heterogeneous biomass feedstocks.

Fountain confined spouted beds address some of the limitations of conventional spouted beds by confining the spout within a cylindrical column, reducing the risk of particle carryover and improving reactor stability. The confined geometry allows for better control of gas-solid interactions and residence times, contributing to enhanced gasification performance. Additionally, fountain confined spouted beds offer flexibility in reactor design and scalability, making them suitable for a range of biomass gasification applications.

In biomass gasification, both spouted beds and fountain confined spouted beds have demonstrated promise for improving syngas quality, increasing process efficiency and reducing tar content. Their unique fluidisation characteristics and ability to handle varying feedstock compositions make them valuable tools for biomass-to-energy conversion. However, further research is needed to optimise reactor design, operating conditions and scale-up strategies to fully harness their potential in commercial biomass gasification systems.

1.3 Entrained Flow Gasifier

Entrained flow gasifiers are beneficial for the operation of large-scale facilities (26). Due to the elevated operating temperature and the utilisation of oxygen as a GA, the conversion of tar compounds during biomass gasification is nearly complete, resulting in significant benefits. However, in small-scale units, the use of air as a GA results in a decrease in temperatures, which in turn leads to an increase in tar content (27). The combination of biomass and water can be utilised as a slurry to aid in the introduction of materials into the reactor (12).

On the other hand, flow gasifiers necessitate the use of finely ground fuel particles (0.1–1 mm). The significant downside of biomass gasification is the substantial energy expenditure required to reduce the size of the biomass (17, 19). Therefore, it is typically necessary to pre-treat biomass using a

Torrefaction process to address the aforementioned drawback (28–30). According to multiple writers, their primary function is to provide biomass and coal as co-gasifiers (31–33).

Entrained flow gasifiers can be classified into two categories: top-fed gasifiers and side-fed gasifiers (13). A top-fed gasifier is a vertical cylindrical reactor where finely crushed particles and GA are simultaneously delivered from the top in the form of a jet. A reversed burner is employed for the purpose of carrying out thermochemical conversion. Syngas is collected from the lateral portion of the lower section, while slag is removed from the base of the reactor (**Figure 4**). In the side-fed gasifier, the pulverised feed and GA are introduced simultaneously through nozzles located in the lower reactor. This arrangement ensures that the biomass and GA are thoroughly mixed to form an appropriate mixture. The syngas is removed from the top of the reactor, while the slag is recovered from the bottom (**Figure 2**).

2. Power Generation Through Gasification

The fuel gas produced from biomass gasification can be utilised for electricity generation using various devices such as gas engines, gas turbines and boilers. In the creation of electricity from gaseous fuels, the preparation of gas for use in an engine or gas turbine is a crucial factor.

The gas obtained from a gasifier exit, which is contaminated, cannot be directly utilised with a gas engine or gas turbine due to potential severe consequences such as cylinder corrosion, flow line blockage, valve blockage, piston choking, blade corrosion and erosion and excessive lubricating oil consumption. Gas conditioning is crucial for attaining the necessary purity of the fuel gas to ensure the efficient functioning of internal combustion engines and gas turbines, in line with the tar concentration limit of less than 100 mg Nm^{-3} (34). However, the gas cleaning system currently lacks strength

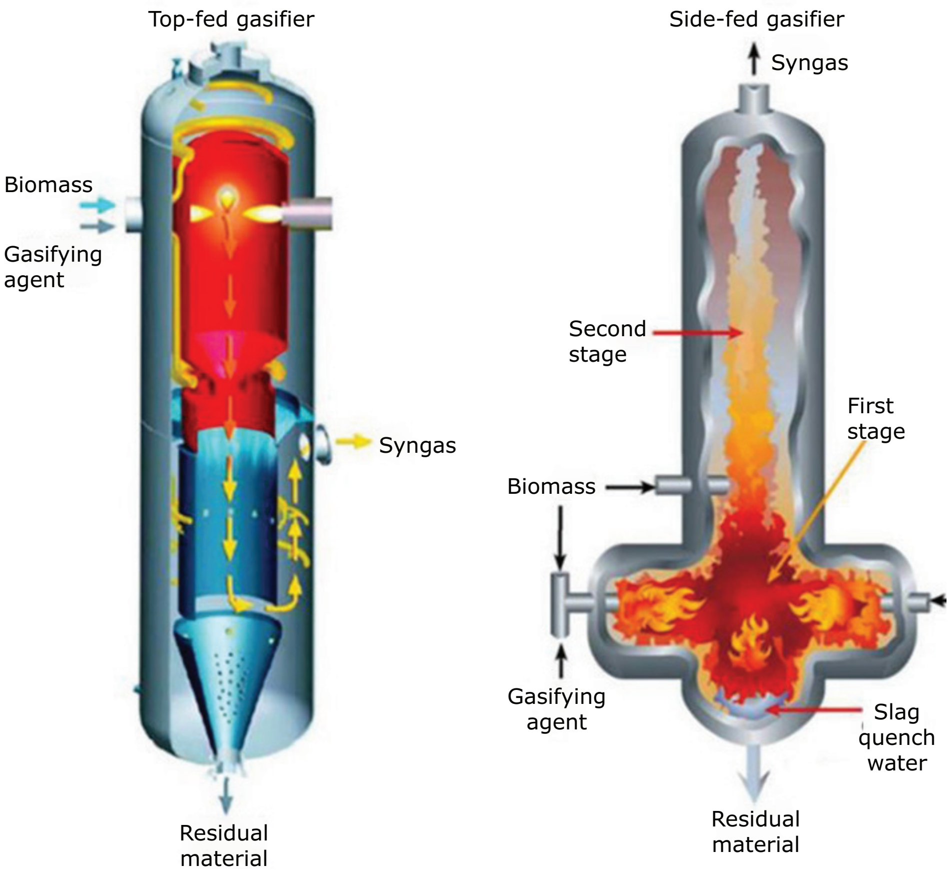

Fig. 4. Entrained flow gasifier schematisation Reprinted from (2) under Creative Commons license 4.0 (CC BY 4.0)

and necessitates ongoing maintenance, resulting in elevated energy generation costs. Conversely, a boiler can be operated without the need for extensive gas purification, allowing the product gas to be used for steam power generation without requiring any specific or severe pretreatment. Steam turbines have demonstrated a total efficiency of less than 20%, while gas turbines and engines can achieve efficiencies as high as 50% (14). The gas engine has garnered significant attention among researchers due to its widespread utilisation in various methods of gas-fuelled power generation. These systems exhibit a low initial investment, low maintenance expenses, low operational costs, limited capacity, sturdy structure and user-friendly operation (35). Engines that run only on producer gas, with a 100% capacity, are not readily accessible in all sizes. Additionally, these engine systems have limited lifespans, leading to various design and maintenance issues (36). Several researchers have studied the process of tar production during gasification, particularly in relation to engine applications (37).

Given the intricacy of the procedure, a definitive resolution to the issue remains elusive. A recent study has explored a unique way to simulating two-phase balances (solid and liquid) to produce high-quality fuel gas. Furthermore, it was highly inadequate to implement a functional grid and coordinate the electricity produced by a gasifier-powered facility that was put into operation in rural regions of India (36). Despite being an established method for power generation, there is still a need for advancements in the commercialisation and development of sustainable bioenergy in developing countries. There are several elements that need to be considered to achieve the required power output of a gas engine. These factors include generating gas heating, determining the composition of the gas mixture and controlling the number of revolutions of the engine (14).

The heating value of the producer gas given to the engine is not constant and depends on the gas composition obtained from the feedstock through gasification. Insufficient air supply might hinder the incomplete combustion of fuel gas, while an excessive volume of air can decrease the heating of fuel gas per unit volume (38). Research (39) found that the heating value of air-diluted producer gas was 2500 kJ m^{-3}, while a stoichiometric mixture of petrol and air had a heating value of 3800 kJ m^{-3}. The quantity of producing gas consumed is contingent upon the volume of the cylinder and the pressure of the gas. Since the volume of the cylinder remains constant, only the inlet pressure conditions are influenced by the quantity of producing gas. A gas mixture increases the input of the producing gas into the cylinder by higher inlet pressure (14). The pressure conditions at the gas input are contingent upon the pressure decrease across the bed area when a gasifier is directly connected to an engine. A decrease in load drop results in a decrease in the amount of fuel gas available at the engine inlet, which has a substantial impact on the engine's power output. A gasification system experiences a slight decrease in pressure within the gasification zone, but the gas combination generated yields significant amounts of tar and pollutants (40, 41).

The engine efficiency is purportedly lower for a specific blend of producer gas and air when compared to a blend of petrol and air. Nevertheless, increasing compression values can effectively restore the lost power of an engine operating on producer gas. Typically, the compression ratio for commercial engines that use fuel gas is between 6.5 and 7.5. However, it is possible to enhance this ratio to as high as ten by enhancing the hydrogen in the producer gas, which results in a faster flame speed (39). A higher compression ratio can result in many problems, such as difficulties in engine ignition, increased vibrations and accelerated piston deterioration, all of which can have a detrimental impact on the lifespan of the engine. Gas turbines have the capacity to handle high-temperature fuel intake, but they are not considered suitable for gas production due to concerns related to dust, particulate matter and alkaline vapour. These factors can lead to corrosion of the turbine blades, unlike commercial engines such as spark ignition and compression ignition engines. Producer gas has demonstrated its significance as a fuel for Sterling engines compared to internal combustion engines due to its low maintenance requirements, low lubricant usage and great thermal efficiency (14).

3. Present State of Gasification Technology

According to Bioenergy Task 33E of The International Energy Agency, the biomass database comprises 114 active biomass gasification facilities globally, 14 idle-to-hold biomass gasification stations and 13 biomass gasification units under development (42–47). Consequently, there is a cumulative count of 141 plants that utilise the syngas generated thereafter (**Figure 5**). There are 106 power

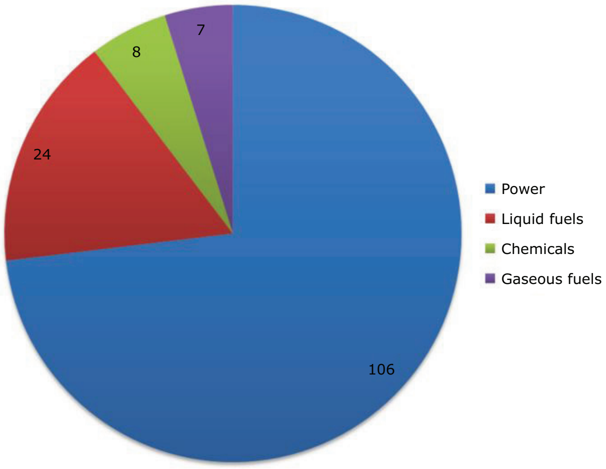

Fig. 5. Number of biomass gasification plants (operational, idle, on hold, under construction or planned) as function of biomass-derived syngas end use (adapted from IEA T33 database (42))

plants worldwide that generate electricity using biomass-derived syngas, with a total capacity of approximately 356 MW. Additionally, there are power plants that produce thermal energy using synthetic gas derived from biomass, with a global capacity of around 185 MW. There are also 24 plants that produce liquid fuels (such as methanol, ethanol, dimethyl ether, Fischer-Tropsch synthesis, diesel and fuel) from biomass-derived syngas, with a global production of approximately 750,000 tonnes per year. Furthermore, there are eight production plants that generate gaseous fuel (synthetic natural gas and hydrogen) from biomass-derived syngas, with a global production of approximately 3.2 × 108 Nm^3 per year. Lastly, there are seven chemical production plants that utilise biomass-derived syngas to produce various chemicals, with a global production of approximately 9000 tonnes per year. It should be underlined that syngas is used to produce both power and fuel in four facilities (48–56).

Through an examination of the operational, idle, under construction, on hold and planned biomass gasification plants for each end use, based on their start-up year (**Figure 5**), it is evident that the utilisation of syngas for power production has experienced significant growth, with the number of plants increasing from 114 to 122–127 between 1985 and 2008. The utilisation rate declined during this era, with only four plants being established in 2016 and two plants in 2017 (57–60). This tendency could also be attributed to the termination of public funding designated for the generation of renewable energy by national governments (61–63). Another emerging pattern can be noted where syngas is utilised as a feedstock to produce liquid fuels. Since 2007, there has been a rise in the quantity of biomass gasification facilities utilised for the conversion of syngas, which is necessary to produce liquid fuel (64–66). The trend exhibits a near-constant pattern over time for both gaseous fuels and chemicals. A new facility was planned in 2018, with a separate plant dedicated to the production of gaseous fuel planned for 2019 (67–69).

Tar abatement is a critical aspect in the design of biomass gasification processes, aiming to mitigate the detrimental effects of tar on downstream equipment and product quality. The main approaches to tar abatement can be categorised into primary and secondary methods. Primary tar abatement techniques focus on minimising tar formation during the gasification process itself. These methods include optimisation of operating parameters such as temperature, residence time and gasification agent ratio to promote complete pyrolysis and minimise tar precursor formation (70). Additionally, the use of catalysts, steam reforming and oxygen-enriched air can facilitate tar cracking reactions, converting tar compounds into lighter, more manageable species (71). Secondary tar abatement methods, on the other hand, involve downstream treatment of the raw syngas to remove tar contaminants. These methods typically include processes such as filtration, scrubbing and catalytic reforming, where tar is separated from the gas stream or chemically converted into more benign compounds (72). By integrating both primary and secondary tar abatement approaches, biomass gasification systems can achieve improved process efficiency, product quality and operational reliability.

4. Future Challenges

The relative position of biomass gasification in comparison to other bioenergy technologies has not been adequately determined, despite its various benefits. Both technological businesses and research organisations, despite government backing, have failed to successfully market and extensively disseminate biomass gasification technologies. This is mostly attributed to the presence of numerous generic impediments that impede the implementation of the technology, outweighing the endeavours undertaken to offer assistance. Obstacles such as institutional, informational, economic, political and market constraints have a similar level of importance and significance in many countries, particularly in poor nations and have an influence on almost all methods of converting biomass. These difficulties involve challenges associated with implementing long-lasting policies aimed at promoting sustainable development by regional government and administrative bodies. The lack of awareness among industry, institutions, local authorities, consumers and entrepreneurs poses a substantial obstacle to the growth of gasification technology, resulting in information barriers. The lack of consistency in knowledge, literacy and credible sources of information is anticipated to further hinder the adoption of biomass energy. Moreover, the distribution of public funds, development of legislation and prioritisation of fossil fuels are essential factors to be considered for the progress of sustainable bioenergy. The biomass gasification market is hindered by its instability and inconsistency, which limits its capacity to demonstrate its promise as a feasible energy source. While biomass gasification holds significant promise as a sustainable energy conversion technology, several challenges must be addressed to ensure its widespread adoption and commercial viability. One of the primary technical barriers is the formation of tar during the gasification process. Tar compounds, produced from the incomplete pyrolysis of biomass, can lead to equipment fouling, reduced efficiency and lower product quality. Developing efficient tar abatement strategies, including primary and secondary tar removal techniques, is essential to mitigate these challenges.

Another critical challenge is the heterogeneity of biomass feedstock, which can vary significantly in composition, moisture content and physical properties. This variability poses challenges for process optimisation and control, as different biomass types may require unique operating conditions for optimal gasification performance. Addressing biomass heterogeneity through advanced feedstock characterisation techniques and adaptive process control strategies will be crucial for ensuring consistent and reliable gasification operations.

Furthermore, the uneven supply of biomass feedstock throughout the year presents logistical and operational challenges for biomass gasification plants. Seasonal variations in biomass availability can lead to fluctuations in feedstock quality, quantity and cost, impacting the economic viability and overall sustainability of gasification processes. Developing strategies for biomass storage, preprocessing and supply chain management to ensure reliable feedstock availability year-round will be essential for overcoming this challenge. Addressing these future challenges in biomass gasification will require interdisciplinary research efforts encompassing materials science, chemical engineering, environmental science and biomass logistics. Collaborative initiatives between academia, industry and government agencies will be essential to drive innovation, develop robust technologies and accelerate the transition towards a more sustainable and resilient bioenergy sector. By overcoming these technical barriers, biomass gasification has the potential to play a significant role in decarbonising the energy sector and advancing global efforts towards a low-carbon future.

According to recent polls, we suggest applying efficient tactics globally in remote and secluded areas to encourage the sustained progress of gasification technology. Multiple issues were categorised as fundamental and can be readily rectified with minimal effort. Through the implementation of economic analysis and the formulation of cost and process characteristics, it is feasible to surmount the technological barriers associated with gas conditioning and use. The establishment of diverse local governing bodies with specific mandates is essential to facilitate the widespread adoption of technology. Developed nations have a responsibility to support poorer nations in addressing climate change caused by the widespread use of fossil fuels, primarily by providing oversight when requested. An effective approach to achieve this objective is to advocate for the adoption of bioenergy technology as feasible alternatives for generating renewable energy. Furthermore, it is crucial to reevaluate governmental regulations to facilitate the wider implementation of the technology. In summary, additional research and infrastructural improvements are required to overcome the barriers that now impede the efficient distribution and commercialisation of biomass gasification technology. The pursuit of sustainable energy sources globally is imperative, particularly considering the United Nations Sustainable Development Goals (UNSDGs), which provide a comprehensive framework for addressing this challenge.

5. Conclusion

This two-part paper provides a thorough analysis of several gasification procedures and the potential

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uses of the generated gasification products. Different biomass gasification techniques, including upstream, gasification and downstream processes, are used to transform biomass. The choice of procedure employed is contingent upon the system and the temperature at which gasification occurs. Syngas is the primary product generated from biomass gasification.

This paper offers an overview of biomass gasification technologies, highlighting their importance in the renewable energy landscape. Unlike other renewable energy sectors that have seen significant advancements, biomass conversion remains relatively nascent, underscoring the importance of staying abreast of new developments. Biomass gasification, a thermochemical conversion process, involves the degradation or incomplete combustion of biomass solid source materials in an oxygen-deficient atmosphere to produce biomass gas. This gas has versatile applications, from powering industrial boilers to providing electricity in underserved areas. By converting biomass into a clean and combustible gas, gasification technology enhances the efficiency of biomass energy utilisation. The focus of this essay is on the methodologies and protocols employed in biomass gasification, recognising its pivotal role in sustainable energy generation.

Addressing fundamental issues through economic analysis and process optimisation can help overcome technological barriers, including gas conditioning challenges. The establishment of local governing bodies with specific mandates is crucial for facilitating widespread technology adoption, with developed nations urged to support less affluent nations in transitioning away from fossil fuels. Advocating for bioenergy technology adoption and revisiting regulatory frameworks are vital steps towards wider implementation. In summary, further research and infrastructure development are necessary to surmount existing barriers hindering the efficient distribution and commercialisation of biomass gasification technology.

Declaration of Competing Interest

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

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