energies

Perspective

Some Perspectives for the Gasification Process in the Energy Transition World Scenario

Eliseu Monteiro [1,2,*] and Sérgio Ferreira [3]

[1] Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[2] LAETA, Associated Laboratory for Energy, Transports and Aeronautics-INEGI, Institute of Science and Innovation in Mechanical and Industrial Engineering, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[3] CT2M—Centre for Mechanical and Materials Technologies, Department of Mechanical Engineering, University of Minho, 4804-533 Guimarães, Portugal; sergiomf@outlook.pt
* Correspondence: emonteiro@fe.up.pt

Abstract: Energy demand has increased over the years due to population growth, industrial, and socio-economic developments, cornerstones of human civilization. Additionally, climate change alarms are placing the energy transition in the top concerns of intergovernmental organizations. Therefore, there are several reasons for concern regarding the need for a new paradigm in the world energy scenario. This perspective article focuses on the contribution that the gasification process may have in the global energy transition scenario. The perspectives for a full world energy transition are that it cannot be accomplished without a transportation fuel transition and an industry transition. Biomass gasification is a sustainable process that allows the production of a large range of commodities such as electricity and heat, biofuels, and chemicals. Meanwhile, some challenges such as tar, impurities, and soot must be overcome or at least limited to an acceptable minimum to promote the economic viability of the gasification plants before they can effectively contribute to the world energy transition. In this regard, further research should be made focused on improving the syngas quality and the economic viability of a biomass gasification plant. This can be achieved by several means including new reactor designs, advanced gasification processes (e.g., plasma gasification and supercritical water gasification), and intensifying the gasification process.

Keywords: energy transition; gasification; hydrogen; biomass

Citation: Monteiro, E.; Ferreira, S. Some Perspectives for the Gasification Process in the Energy Transition World Scenario. *Energies* **2023**, *16*, 5543. https://doi.org/10.3390/en16145543

Academic Editor: Fernando Rubiera González

Received: 8 April 2023
Revised: 18 July 2023
Accepted: 20 July 2023
Published: 22 July 2023

1. Introduction

Energy demand has increased over the years due to population growth, and industrial and socio-economic developments, cornerstones of human civilization. As fossil fuels have been the basis of energy supply worldwide, they are linked with climate change and global warming. In addition to the protection of the environment, the depletion of fossil fuel resources is an important aspect that needs to be overcome. Consequently, using alternative energy sources to reduce climate change is a primary concern nowadays [1]. According to international energy agencies, energy production and use account for about two-thirds of worldwide greenhouse gas emissions, placing the energy sector at the heart of climate change programs.

As a result, the energy sector is under a lot of regulatory pressure, facing increased competition, and being asked to provide environmentally friendly and ecologically responsible solutions. For these reasons, the energy transition is among the top concerns of intergovernmental organizations such as the "Intergovernmental Panel on Climate Change, the International Energy Agency, and the International Renewable Energy Agency", which play a critical role in the global alignment of emission-reduction strategies and will undoubtedly be critical as we attempt to achieve net zero emissions by 2050. Additionally, the United Nations foresees that the world's population will attain almost 10 billion by 2050. This population growth, together with the expected rise in living standards, will result in a more intense demand for energy. For these reasons, numerous nations have begun to establish plans to deal with the negative impacts of global warming. Many nations have started to rearrange their energy sources because energy is the primary cause of carbon emissions. Nuclear and renewable energy are seen to be the most effective carbon-free energy sources and have garnered interest on a global scale [2].

As a result, governments around the world are revisiting their energy strategies to enable transition mainly towards increased adoption of renewable energy sources. Therefore, there has been an increase in interest in the idea of switching from conventional energy sources to some cleaner, greener options. The International Renewable Energy Agency has recognized the importance of the transition to clean energy, claiming that the global energy sector has switched from non-renewable to renewable sources, achieving the goal of a 90% reduction in carbon emissions. Due to this, the switch to renewable energy has closed any existing or anticipated future energy supply and demand gaps, providing a path towards carbon neutrality [3].

As a matter of example, renewable energy experienced the fastest growth between 2010 and 2021, with an average annual growth rate of 0.8 percentage points, and its total share of global power generation in 2021 was 28.7%. Renewables are critical to clean energy transitions, and renewable power deployment is one of the primary enablers of keeping the rise in average world temperatures below 1.5 °C. However, to achieve net zero emissions by 2050, renewable electricity must rise faster, with the renewable share of generation increasing from about 29% in 2021 to more than 60% by 2030. The main contributions are anticipated to come from wind and solar energy. Nevertheless, bioenergy should almost double its contribution in electricity generation from 764.2 TWh in 2021 to 1386.8 TWh in 2030, which represents an average growth rate of around 7% per year [4]. Given that lignocellulosic biomass is the most abundant biomass on the globe, annual production is expected to be 181.5 billion t. There are 8.2 billion t in usage, with around 7 billion t coming from agricultural and forest sources and the remaining 1.2 billion t deriving from agricultural waste [5]. This biomass potential is yet to be explored to a larger extent to make it possible to achieve the 2050 goals. Biomass conversion into energy can be achieved by a handful of established processes. Among them, biomass gasification is the most promising [6]. Its principal advantage stems from the significantly higher temperatures used, which results in superior quality and cleaner syngas due to the sharp elimination of unwanted impurities. Indeed, the increasing environmental regulations imposed by governments and international organizations promote the high efficiency provided by gasification [7].

The biomass gasification system provides low-cost, exceptional decentralized energy sources compared to a typical gas-powered system. Additionally, coupling biomass gasification with gas and steam turbines forms a highly efficient and clean biomass system for generating heat and electricity.

Currently, Europe is leading the biomass gasification market mainly due to the contributions of Germany and Sweden [8]. It is expected that highly populated countries such as China and India will contribute to the progress in the biomass gasification market mainly due to their huge increasing electricity demands. The increasing rate of rural electrification, particularly in emerging economies, has also raised the necessity for decentralized energy production. This motivation can be considered one of the major drivers of the worldwide biomass gasification market's growth [9].

The development of technologies has also been continuously funded by the major market participants as well as the governments of various countries, contributing to the market's sustained expansion. Moreover, the intensive research and development of biomass gasification processes also positively influences the global market. The global gasification market is valued at USD 114.1 billion in 2021 and expected to reach USD 209.63 billion by 2029 [10]. This prediction is based on a market compound annual growth rate of 7.9% if the current innovations in the sector continue.

As seen, there are several reasons for concern regarding the need for a new paradigm in the world energy scenario. This perspective article focuses on some of the contributions that the gasification process may have in the global energy transition scenario. The next sections can be described as follows. In Section 2, the gasification process is briefly described, pointing out the main advantages and constraints that remain to be investigated as well as the main applications for syngas. Section 3 describes the future directions that, in the opinion of the authors, should be followed to increase the market penetration of gasification technology. In Section 4, the main conclusions of this perspective are summarized.

2. Conventional Gasification Process

Conventional gasification is globally an endothermic process, which means that heat is required to support the process. Figure 1 shows that the gasification process can be autothermal or allothermal, depending on how the heat is supplied. In an autothermal gasification process, the heat is generated by partial oxidation within the reactor. In an allothermal gasification process, the required heat is provided by an external source [11]. The term allothermal has its origin in the Greek word “allos” meaning “other”.

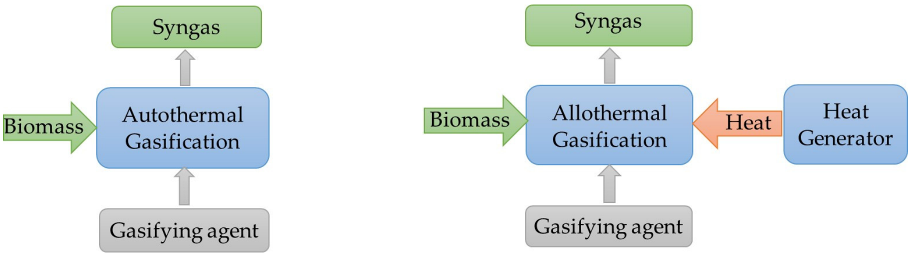

Figure 1. Autothermal gasification versus allothermal gasification.

Gasification is a thermochemical conversion process of a carbon-based fuel at high temperature, which might include partial oxidation of the converted combustible elements [12]. The result of the air-blown autothermal gasification is a combustible gas containing hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen, some light hydrocarbons (ethyne, ethene, ethane, etc.), residual poisonous gases (hydrogen cyanide, hydrogen sulfide, ammonia, etc.), and impurities such as char, tar, and ash.

The autothermal gasification process occurs in a single reactor (or gasifier), in the presence of an oxidizing agent, mandatorily containing the oxygen needed for partial oxidation reactions. They might be pure oxygen, air, or blends of these with steam or carbon dioxide. In an allothermal gasification process, the presence of oxygen is not allowed, and pure gasifying agents are used, such as steam or carbon dioxide.

Inside the reactor of an autothermal gasification process, a set of four processes take place at the same time and are generally designated as drying, pyrolysis, oxidation, and reduction [13]. In the case of allothermal gasification, only three processes occur simultaneously: drying, pyrolysis, and reduction. Since there is no oxygen inside the reactor, all the oxidation reactions will not occur, which means that the necessary heat for the endothermic reactions does not come from the oxidation phase but is generally transferred to the gasification through heat exchangers or with a heat carrier such as a bed material in fluidized bed reactors. The quality of the syngas depends on various gasification factors including type of feedstock, gasifier type, and operational conditions. In the next subsections, the most important of these are discussed.

2.1. Effect of Feedstock Characteristics

According to Alves et al. [14], impurities in the feedstocks and incomplete gasification result in pollutants in the generated syngas. They are mostly categorized as tars, particle matters, alkali, nitrogen (hydrogen cyanide, ammonia), sulfur (hydrogen sulfide, carbonyl sulfide), and halides. These contaminants are responsible for downstream issues in the gasifier including corrosion, blockage, and catalyst deactivation. Moreover, they also make syngas inappropriate for various applications such as Fischer–Tropsch synthesis, fuel cells, and methanol production. They necessitate syngas processing prior to its use. Table 1 summarizes the main impurities that can be present in the syngas, the associated issues, and the cleanup methods for their elimination.

Table 1. Syngas impurities, associated problems, and cleanup methods [15,16].

Impurity	Examples	Issues	Cleanup Method
Particulates	Ash, char, bed material	Erosion	Filtration, scrubbing
Alkali metals	Sodium and potassium compounds	Corrosion	Cooling, condensation, filtration, adsorption
Nitrogen components	NH_3 e HCN	NO_x formation	Scrubbing, selective catalytic reduction
Tars	Aromatics	Clog filters, difficult to burn, deposit internally	Tar cracking; tar removal
Sulfur, Chloride	H_2S, HCl	Corrosion, emissions	Lime or dolomite scrubbing or absorption

A recent review of Ramos et al. [17] on biomass pretreatment techniques clearly presents the motives for the application of pretreatment processes prior to its conversion. Regarding the gasification process, the main pretreatment methods applied are grinding/milling, drying, torrefaction, and densifying techniques. These findings clearly express the desirable characteristics of the feedstock for the conventional gasification process. These are:

- Biomass particle dimensions, which are reactor-dependent (5–100 mm for fixed bed reactors, 6–50 mm for fluidized bed reactors, and <1 mm for entrained flow reactors [18]) and have a great influence on the gasification rate. Smaller particles can mix with each other and to willingly fit into any remaining space, boosting the overall energy efficiency of the gasification process. However, their size reduction incurs an additional expense due to the necessary milling/grinding pretreatment. Moreover, smaller particles increase the yields of hydrogen and syngas as well as the carbon conversion [19]. However, they should respect the gasifier and feeding system limitations to prevent agglomeration. The fibrous biomass frequently becomes stuck in the feeding system. These problems can be overcome by densifying the biomass, which reduces the spaces between particles and thus increases the bulk density.
- Low moisture, low sulfur, and low chlorine contents. Feedstocks with higher moisture necessitate drying prior to the gasification stage. Increased moisture content increases hydrogen while decreasing carbon monoxide, owing to the consumption of this latter component in the water–gas shift reaction. Yet, because carbon monoxide has a higher heating value than H_2, the drop in carbon monoxide yield has a greater impact than the increase in hydrogen production, resulting in a negative balance in syngas quality. Typical moisture requirements for downdraft reactors are below 12%, <40% for updraft reactors, and between 10% and 60% for fluidized bed reactors [18]. Sulfur content is usually residual (<0.1%) in lignocellulosic biomasses. However, the presence of this compound gives rise to SO_2 formation, enhancing the corrosion potential of the process [20].
- Chlorine can also be present in some lignocellulosic biomasses but in residual amounts (<0.1%) and must the submitted to dichlorination prior to the gasification process [18]. This chlorine would lead to the formation of chlorine acid (Cl_2), enhancing the corrosion potential of the process.
- Ash content and melting temperature are also a fundamental biomass characteristics from thermal conversion. However, the ash fusion temperatures of the biomass ash oscillate from 1100 °C to 1300 °C [21], which is generally above the temperature range of the conventional gasification processes, thus preventing the melting of the

inorganics and allowing some of them to act as catalysts in fluidized bed reactors such as potassium and sodium.

2.2. Effect of Gasifying Agent

Air, steam, oxygen, and, more recently, carbon dioxide are the typical gasifying agents utilized in biomass gasification. The following significant findings have been reached after studies on each of them:

- Due to its low cost, air is the main gasifying agent, with the resulting syngas being heavily diluted by nitrogen (about 50%) and having a lower heating value (typically 4–6 MJ/m^3) and hydrogen concentration below 20% [22]. To improve the syngas quality, air has been used combined with steam and pure oxygen (oxygen-enriched air). Hernandez et al. [23] demonstrated that the use of a mixture of air and steam as the gasifying agent enhances the quality of the syngas, increasing its hydrogen and methane contents. Ismail et al. [7] showed that the use of oxygen-enriched air allows the production of a syngas with a reasonable heating value (around 9–15 MJ/m^3); however, this has the shortcoming of being more costly once oxygen separators from air are needed.
- Steam use for biomass gasification allows obtaining a syngas with a higher heating value (typically 10–18 MJ/m^3) and hydrogen content [24], although an external source of heat is required to increase the temperature of the process (allothermal gasification). Steam gasification also has the advantage of operating with both wet and dry biomass [19]. The review of Ahmad et al. [19] also presents the use of a mixture of steam and pure oxygen to promote biomass conversion, accompanied by a carbon dioxide increase and the decrease of carbon monoxide and hydrogen.
- Pure oxygen usage as a gasifying agent in biomass gasification systems was reviewed by Mishra and Upadhyay [25]. They conclude that an improved gasification as well as enhanced carbon conversion, and a heating value between 10 and 18 MJ/m^3 was obtained, mainly because of the absence of nitrogen in the gasifying medium. However, due to the separation of oxygen from the air, oxygen-blown gasification is an energy-intensive and expensive process.
- Carbon dioxide is the least studied gasifying agent. A recent review by Chan et al. [26] concluded that the use of carbon dioxide as the gasifying agent provides a syngas rich in carbon monoxide (40–80 vol. %), essentially because of the dominant Boudouard reaction that is only thermodynamically active over 700 °C. Carbon dioxide gasification is a very promising conversion method that takes advantage of the abundance of carbon dioxide and biomass to generate value-added carbon monoxide. The successful commercialization of this method would have a significant impact on achieving the UN Sustainable Development Goals and the Paris Climate Agreement.

2.3. Syngas Applications

Syngas applications may be divided according to the commodities it can generate such as fuels, chemicals, heat, and power. These are discussed in the next subsections.

2.3.1. Heat and Power

Producing power from gasified biomass has been increasingly used worldwide. Biomass gasification is a direct route to extract energy from renewable resources efficiently and is one of the most suitable processes for combined heat and power (CHP) production. The integration of the biomass gasification process with a gas engine for CHP production has high power efficiency potential that can reach 40% [27].

When a biomass gasification system is integrated with a gas turbine (Brayton Cycle) and a steam turbine (Rankine cycle), the system is known as biomass integrated gasification combined cycle (BIGCC) system [28]. These systems are considered some of the most efficient technologies for large-scale power generation based on gaseous fuels [29]. However, the viability of BIGCC technology in power generation has yet to be proven because of the succession of projects mothballed for economic reasons (e.g., the Värnamo IGCC plant in Sweden and the Güssing CHP gasification plant in Austria).

2.3.2. Fuels

Various synthetic fuels can be produced from syngas via the Fischer–Tropsch process [30]. Fischer–Tropsch synthesis involves the catalytic reaction of hydrogen and carbon monoxide to form hydrocarbon chains of various lengths according to the general synthesis reaction in Equation (1):

$$(n/2 + m)\, H_2 + m\, CO \rightarrow C_mH_n + m\, H_2O \tag{1}$$

Cobalt, iron, nickel, and ruthenium have been identified as active catalysts for the Fischer–Tropsch synthesis reaction [31]. However, only cobalt and iron exhibit sufficient carbon monoxide hydrogenation for industrial Fischer–Tropsch plants since ruthenium is much more expensive, and nickel favors methane formation and produces nickel carbonyl which readily deactivates the catalyst. Iron, a reasonably inexpensive and versatile catalyst for a variety of operating conditions, enhances the water–gas shift reaction during Fischer–Tropsch synthesis, which allows the use of syngas with low-hydrogen content. Syngas with H_2/CO ratios of 0.5 to 0.7 are recommended for iron catalysts. Cobalt catalysts, on the other hand, are significantly more active than iron-based catalysts, but are 250 times more expensive, hence they are typically used as a support catalyst [32]. There are various commercial Fischer–Tropsch plants in South Africa producing about 150,000 barrels per day of gasoline, diesel, and jet fuel from coal gasification [33].

Hydrogen is rising in the energy transition scenario as an important energy carrier able to replace fossil fuels [34]. Biomass gasification is emerging as a cost-effective, cleaner, and sustainable process of producing hydrogen at 1.77–2.77 $/kg [35,36]. However, to obtain pure hydrogen from a gasification process, there are some additional operational units that should be included (Figure 2).

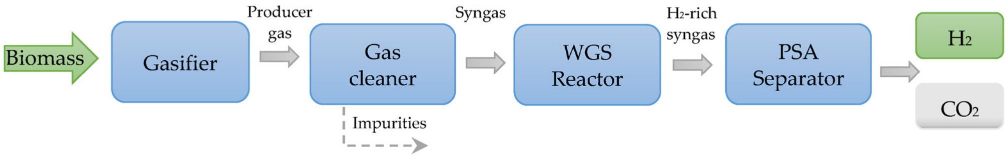

Figure 2. Process flow diagram of biomass gasification for pure hydrogen production.

The gas coming from the gasifier must be cleaned from impurities such as tar and ashes to be transformed into a syngas containing only CO and H_2. This syngas is supplied to a water–gas-shift (WGS) reactor in order to increase the hydrogen content of the gas. This reactor produces H_2 and CO_2, so another operational unit must be used to separate these gases. The pressure swing absorption (PSA) separation unit allows us to obtain pure H_2.

2.3.3. Chemicals

Syngas can be used to make petrochemicals and ammonia, which can then be used in agricultural fertilizers. The most significant advantage of syngas is that it can be directly converted to a variety of important chemical products (methanol, di-methyl ether, and olefins) that would otherwise be produced from natural gas. The chemical industry provides key materials to the cosmetics, pharmaceutical, and plastic packaging sectors. Syngas was initially utilized in ammonia and methanol plants. China is manufacturing syngas from small coal-fired power stations, which will be processed into ammonia and used to make fertilizer. China's synthetic ammonia industry has the world's greatest capacity and volume of production, with a total production of 57.58 Mt in 2019 [37]. Table 2 summarizes desirable syngas characteristics for various end-use options.

Table 2. Desirable syngas characteristics for different applications [15,38].

Product/Property	Fischer–Tropsch Synthesis	Methanol	Hydrogen	Heat and Power	
				Boiler	Turbine
H_2/CO	0.6 (a)	∼2.0	High	Irrelevant	Irrelevant
CO_2	Low	Low (c)	Unimportant (b)	Not critical	Not critical
Hydrocarbons	Low (d)	Low (d)	Low (d)	High	High
N_2	Low	Low	Low	(e)	(e)
H_2O	Low	Low	High (f)	Low	(g)
Contaminants	<1 ppm sulfur Low particulates	<1 ppm sulfur Low particulates	<<1 ppm sulfur Low particulates	(k)	Low particulates and metals
Heating value	Irrelevant (h)	Irrelevant (h)	Irrelevant (h)	High (i)	High (i)
Pressure (bar)	∼20–30	∼50 (liquid phase) ∼140 (vapor phase)	∼28	Low	∼400
Temperature (°C)	200–300 (j) 300–400	100–200	100–200	250	500–600

(a) Depends on the catalyst type. For iron catalysts, the value shown is satisfactory; for cobalt catalysts, a value near 2.0 should be used. (b) Water–gas shift will have to be used to convert CO to H_2; CO_2 in syngas can be removed at the same time as CO_2 is generated by the water–gas shift reaction. (c) Some CO_2 could be tolerated if the H_2/CO ratio remains above 2.0; if an excess of H_2 is available, the CO_2 will be converted to methanol. (d) Methane and heavier hydrocarbons need to be recycled for conversion to syngas and represent system inefficiency. (e) N_2 lowers the heating value, but its percentage is not important if syngas can be burned with a stable flame. (f) Water is required for the water–gas shift reaction. (g) Can tolerate relatively high water levels; steam is sometimes added to moderate combustion temperatures to control NOx. (h) As long as the H_2/CO ratio and impurity levels are met, the heating value is not critical. (i) Efficiency improves as the heating value increases. (j) Depending on the catalyst type, iron catalysts typically operate at temperatures higher than cobalt catalysts. (k) Small amounts of contaminants can be tolerated.

Syngas properties and conditioning are generally more important for fuels and chemical synthesis applications than for hydrogen and fuel gas uses. A high purity synthetic gas is highly advantageous for fuels and chemical synthesis since it significantly decreases the size and expense of downstream equipment. However, the syngas characteristics provided in Table 2 should not be interpreted as strict requirements. Supporting process equipment can be employed to adjust the syngas quality to match those optimal for the target end-use, but at an increased complexity and cost.

3. Some Future Perspectives for the Gasification Process

The gasification process has already climbed a long hill, but several constraints remain to be overcome for a more effective penetration into the world's energy mix. The description made in Section 2 allows us to better frame what the role of the gasification process may be in the global energy scenario. The main outcomes that can be retrieved are summarized in Figure 3.

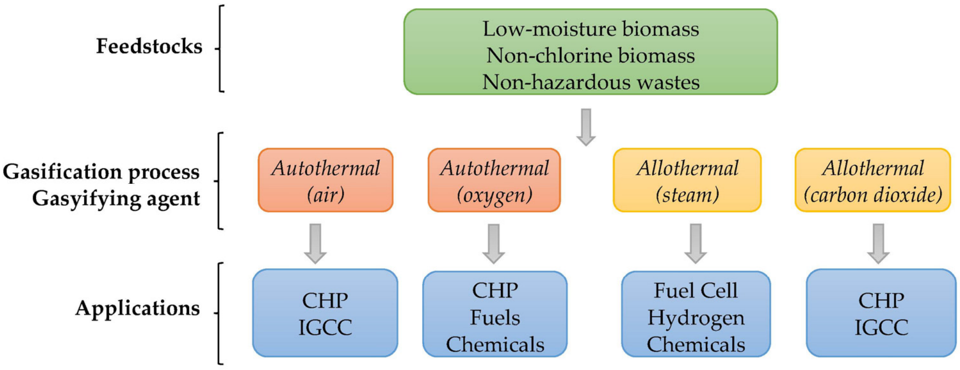

Figure 3. Conventional gasification process required inputs and main outputs.

It clearly shows that the feedstocks most appropriate for each gasification process differ substantially. Although the conventional gasification process is less complex and more economical, it is limited to low-moisture lignocellulosic biomasses and non-chlorine and non-hazardous wastes due to process limitations.

These "complex" wastes can be converted into syngas by using special (and expensive) gasification methods such as plasma gasification for hazardous wastes as expressed in Oliveira et al. [39], or supercritical water gasification for high-moisture biomasses as expressed by Hu et al. [40].

The outputs are dependent on the gasifying medium used. When the performances of those gasifying agents on the gasification of biomass are compared, the conclusions show that pure steam performed better in terms of operational settings and syngas composition (higher H_2 yields and LHV). CO_2 gasification could provide a carbon-neutral solution to the two key increasing issues of energy security and global warming. The use of CO_2 by itself or with air/steam as a gasifying agent can cause the reaction products to contain more CO.

Biomass gasification has several problems that prevent the effective application at a commercial stage. These are primarily related to the variability of the biomass characteristics requiring energy and labor-intensive pretreatment processes such as drying, grinding and densification, and the producer gas conditioning, especially the cleaning of tars and ashes which is problematic and cost-intensive [17]. The technology readiness level (TRL) for biomass gasification is still around seven, which means that this technology is not yet mature enough to be commercialized [34]. For these reasons, biomass gasification must be further investigated in the following aspects [41]:

- Optimizing and comprehending the behavior of the reactor, because it is the least efficient piece of a gasification plant. Its design and operation require a thorough understanding of the gasification process and how the design, feedstock, and key operating settings have an impact on entire performance.
- Efficient and cost-effective gas cleaning systems for the downstream application of syngas. Gas cleaning is required to avoid erosion, corrosion, and environmental issues in downstream applications. Tars are generally heavy hydrocarbons produced by the biomass gasification process, which can clog engine valves or cause turbine fouling, resulting in greater maintenance costs and reduced performance. Tars also interfere with the production of fuels and chemicals.

The technical issues of a biomass gasification plant can be overcome through research and development. However, there are also economic issues that prevent its commercial progress. The reasons for the economic failure are beyond the scope of this work but can be expressed as capital expenditures and operational expenditures of a gasification plant.

The future directions for the development of biomass gasification power plants should be focused on the demonstration of their economic viability. This should be done through demonstration gasification plants incorporating the most recent developments in the various operating units, especially in the gas cleaning unit, which is considered the most expensive operation unit in a biomass gasification facility. Another economic barrier to the development of biomass gasification plants is the high cost of long-distance biomass transportation. The solution to reducing biomass transportation costs is to implement gasification facilities on a small-to-medium scale.

If the biomass gasification plant is intended to produce hydrogen, it has been demonstrated that, from a technical standpoint, the supercritical water gasification process yields the most hydrogen. However, from an economic point of view, conventional gasification achieves better performance [36].

The perspectives for the economic viability of a biomass gasification plant producing hydrogen can be expressed as the need to improve the technical and economic performance of the gasification processes in producing hydrogen. Water–gas shift technology, which uses the carbon monoxide present in syngas to improve hydrogen generation, can be added to biomass gasification plants. Another upgrade suggestion is to separate the carbon dioxide produced during the gasification process, which is then mixed with steam as the gasifying agent and supplied into the gasifier. This raises the carbon monoxide content of the syngas, which may function as a reactant in the water–gas shift process, increasing the amount of hydrogen produced. Moreover, carbon dioxide is maintained in the gasification process, resulting in a carbon-negative gasification plant.

4. Conclusions

The world energy transition cannot be fully accomplished without a transportation fuel transition and an industry transition.

Biomass gasification is an environmentally friendly method for producing power, biofuels, chemicals, and heat. As a result, by turning biomass into useful materials, energy, or biofuels, including hydrogen, biomass gasification can theoretically contribute to the world energy transition. Unfortunately, various obstacles, including tar, impurities, and soot, have made its industrial development challenging. These challenges must be overcome or at least limited to an acceptable minimum to promote the economic viability of the gasification plants before they can effectively contribute to the world energy transition. In this regard, further research should be focused on improving the syngas quality and the economic viability of a biomass gasification plant. This can be achieved by several means including new reactor designs, advanced gasification processes (e.g., plasma gasification and supercritical water gasification), and intensifying the gasification process to increasing the hydrogen yields. Long-distance biomass transportation is another economic issue of large-scale biomass gasification plants that can be overcome by implementing small- to medium-scale gasification plants.

Author Contributions: Conceptualization, E.M.; methodology, S.F.; investigation, E.M. and S.F; resources, E.M.; writing—original draft preparation, S.F.; writing—review and editing, E.M.; project administration, E.M.; funding acquisition, E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Portuguese Foundation for Science and Technology (FCT) under the project n.º 2022.08625.PTDC.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Monteiro, E.; Ferreira, S. Biomass Waste for Energy Production. *Energies* **2022**, *15*, 5943. [CrossRef]
2. Danish, R.; Ozcan, U.B. An empirical investigation of nuclear energy consumption and carbon dioxide (CO_2) emission in India: Bridging IPAT and EKC hypotheses. *Nucl. Eng. Technol.* **2021**, *53*, 2056–2065. [CrossRef]
3. Gielen, D.; Francisco, B.; Deger, S.; Morgan, D.B.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]
4. IEA, Bioenergy, IEA, Paris. License: CC BY 4.0. 2022. Available online: https://www.iea.org/reports/bioenergy (accessed on 5 May 2023).
5. Dahmen, N.; Lewandowski, I.; Zibek, S.; Weidtmann, A. Integrated lignocellulosic value chains in a growing bioeconomy: Status quo and perspectives. *CBC Bioenergy* **2019**, *11*, 107–117. [CrossRef]
6. Ferreira, S.; Monteiro, E.; Brito, P.; Vilarinho, C. Biomass resources in Portugal: Current status and prospects. *Renew. Sustain. Energy Rev.* **2017**, *78*, 1221–1235. [CrossRef]
7. Ismail, T.; Ramos, A.; Monteiro, E.; El-Salam, M.; Rouboa, A. Parametric studies in the gasification agent and fluidization velocity during oxygen-enriched gasification of biomass in a pilot-scale fluidized bed: Experimental and numerical assessment. *Renew. Energy* **2020**, *147*, 2429–2439. [CrossRef]
8. Situmorang, Y.A.; Zhao, Z.; Yoshida, A.; Abudula, A.; Guan, G. Small-scale biomass gasification systems for power generation (<200 kW class): A review. *Renew. Sustain. Energy Rev.* **2020**, *117*, 109486.
9. Lanjekar, P.R.; Panwar, N.L.; Agrawal, C. A comprehensive review on hydrogen production through thermochemical conversion of biomass for energy security. *Bioresour. Technol. Rep.* **2023**, *21*, 101293. [CrossRef]
10. MMR, Maximize Market Research, Biomass Gasification Market—Global Industry Analysis and Forecast (2022–2029) by Fuel Type, Applications, and by Region, MMR, India. 2022. Available online: https://www.maximizemarketresearch.com/market-report/biomass-gasification-market/66858/ (accessed on 30 May 2023).
11. Ferreira, S.; Monteiro, E.; Brito, P.; Costa, C.; Calado, L.; Vilarinho, C. Experimental analysis of brewers´ spent grains steam gasification in an allothermal batch reactor. *Energies* **2019**, *12*, 912. [CrossRef]

12. Bourguig, O.; Ramos, A.; Bouziane, K.; Asbik, M.; Monteiro, E.; Rouboa, A. Performance assessment of the co-gasification for sustainable management of municipal solid waste: Moroccan Case. *Energy Rep.* **2022**, *8*, 1530–1540. [CrossRef]
13. Witold, M.L.; Ryms, M.; Kosakowski, W. Thermal Biomass Conversion: A Review. *Processes* **2020**, *8*, 516.
14. Alves, O.; Monteiro, E.; Brito, P.; Gonçalves, M. Clean-up treatments for syngas obtained by gasification of coal, lignocellulosic biomass or municipal residues. *Prog. Ind. Ecol.* **2022**, *15*, 128–161. [CrossRef]
15. Woolcock, P.J.; Brown, R.C. A review of cleaning technologies for biomass-derived syngas. *Biomass Bioenergy* **2013**, *52*, 54–84. [CrossRef]
16. Khosravani, H.; Rahimpour, H.R.; Rahimpour, M.R. Characteristics of syngas impurities; Physical and chemical properties. In *Advances in Synthesis Gas: Methods, Technologies and Applications*; Rahimpour, M.R., Makarem, M.A., Meshksar, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Volume 2, pp. 3–25.
17. Ramos, A.; Monteiro, E.; Rouboa, A. Biomass pre-treatment techniques for the production of biofuels using thermal conversion methods—A review. *Energy Convers. Manag.* **2022**, *270*, 116271. [CrossRef]
18. Dai, J.; Cui, H.; Grace, J.R. Biomass feeding for thermochemical reactors. *Prog. Energy Combust. Sci.* **2012**, *38*, 716–736. [CrossRef]
19. Ahmad, A.A.; Zawawi, N.A.; Kasim, F.H.; Inayat, A.; Khasri, A. Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1333–1347. [CrossRef]
20. Elbersen, W.; Lammens, T.M.; Alakangas, E.A.; Annevelink, B.; Harmsen, P.; Elbersen, B. Chapter 3—Lignocellulosic Biomass Quality: Matching Characteristics with Biomass Conversion Requirements. In *Modeling and Optimization of Biomass Supply Chains*; Panoutsou, C., Ed.; Academic Press: London, UK, 2017; pp. 55–78.
21. Zhai, M.; Li, X.; Yang, D.; Ma, Z.; Dong, P. Ash fusion characteristics of biomass pellets during combustion. *J. Clean. Prod.* **2022**, *336*, 130361. [CrossRef]
22. Sansaniwal, S.; Pal, K.; Rosen, M.; Tyagi, S. Recent advances in the development of biomass gasification technology: A comprehensive review. *Renew. Sustain. Energy Rev* **2017**, *72*, 363–384. [CrossRef]
23. Hernandez, J.J.; Aranda, G.; Barba, J.; Mendoza, J.M. Effect of steam content in the air-steam flow on biomass entrained flow gasification. *Fuel Process. Technol.* **2012**, *99*, 43–55. [CrossRef]
24. Kuo, P.C.; Wu, W. Design, optimization and energetic efficiency of producing hydrogen-rich gas from biomass steam gasification. *Energies* **2015**, *8*, 94–110. [CrossRef]
25. Mishra, S.; Upadhyay, R.K. Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters. *Mater. Sci. Energy Technol.* **2021**, *4*, 329–340. [CrossRef]
26. Chan, Y.H.; Rahman, S.F.S.A.; Lahuri, H.M.; Khalid, A. Recent progress on CO-rich syngas production via CO_2 gasification of various wastes: A critical review on efficiency, challenges and outlook. *Environ. Pollut.* **2021**, *278*, 116843. [CrossRef] [PubMed]
27. Ahrenfeldt, J.; Thomsen, T.P.; Henriksen, U.; Clausen, L.R. Biomass gasification cogeneration- A review of state of the art technology and near future perspectives. *Appl. Therm. Eng.* **2013**, *50*, 1407–1417. [CrossRef]
28. Ge, H.; Zhang, H.; Guo, W.; Song, T.; Shen, L. System simulation and experimental verification: Biomass-based integrated gasification combined cycle (BIGCC) coupling with chemical looping gasification (CLG) for power generation. *Fuel* **2019**, *241*, 118–128. [CrossRef]
29. Escudero, M.; Gonzalez, C.; Lopez, I. Quantitative analysis of potential power production and environmental benefits of biomass integrated gasification combined cycles in the European Union. *Energy Policy* **2013**, *53*, 63–75. [CrossRef]
30. Oliveira, D.C.; Lora, E.S.; Venturini, O.J.; Maya, D.M.Y.; Garcia-Pérez, M. Gas cleaning systems for integrating biomass gasification with Fischer-Tropsch synthesis—A review of impurity removal processes and their sequences. *Renew. Sustain. Energy Rev.* **2023**, *172*, 113047. [CrossRef]
31. Mirzaei, A.A.; Arsalanfar, M.; Bozorgzadeh, H.R.; Samimi, A. A review of Fischer-Tropsch synthesis on the cobalt based catalysts. *Phys. Chem. Res.* **2014**, *2*, 179–201.
32. Okoye-Chine, C.G.; Moyo, M.; Liu, X.; Hildebrandt, D. A critical review of the impact of water on cobalt-based catalysts in Fischer-Tropsch synthesis. *Fuel Process. Technol.* **2019**, *192*, 105–129. [CrossRef]
33. Kanwal, S.; Mehran, M.T.; Hassan, M.; Anwar, M.; Naqvi, S.R.; Khoja, A.H. An integrated future approach for the energy security of Pakistan: Replacement of fossil fuels with syngas for better environment and socio-economic development. *Renew. Sustain. Energy Rev* **2022**, *156*, 111978. [CrossRef]
34. Monteiro, E.; Brito, P. Hydrogen supply chain: Current status and prospects. *Energy Storage* **2023**, e466. [CrossRef]
35. Malik, F.R.; Yuan, H.-B.; Moran, J.C.; Tippayawong, N. Overview of hydrogen production technologies for fuel cell utilization. *Eng. Sci. Technol. Int. J.* **2023**, *43*, 101452.
36. Martins, A.H.; Rouboa, A.; Monteiro, E. On the green hydrogen production through gasification processes: A techno-economic approach. *J. Clean. Prod.* **2023**, *383*, 135476. [CrossRef]
37. Zhao, F.; Fan, Y.; Zhang, S.; Eichhammer, W.; Haendel, M.; Yu, S. Exploring pathways to deep de-carbonization and the associated environmental impact in China’s ammonia industry. *Environ. Res. Lett.* **2022**, *17*, 045029. [CrossRef]
38. Abdoulmoumine, N.; Adhikari, S.; Kulkarni, A.; Chattanathan, S. A review on biomass gasification syngas cleanup. *Appl. Energy* **2015**, *155*, 294–307. [CrossRef]
39. Oliveira, M.; Ramos, A.; Ismail, T.; Monteiro, E.; Rouboa, A. A Review on Plasma Gasification of Solid Residues: Recent Advances and Developments. *Energies* **2022**, *15*, 1475. [CrossRef]

40. Hu, Y.; Gong, M.; Xing, X.; Wang, H.; Zeng, Y.; Xu, C.C. Supercritical water gasification of biomass model compounds: A review. *Renew. Sustain. Energy Rev.* **2020**, *118*, 109529. [CrossRef]
41. Shahabuddin, M.; Krishna, B.B.; Bhaskar, T.; Perkins, G. Advances in the thermo-chemical production of hydrogen from biomass and residual wastes: Summary of recent techno-economic analyses. *Bioresour. Technol.* **2020**, *299*, 122557. [CrossRef]