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Article

Sustainable Hydrogen from Biomass: What Is Its Potential Contribution to the European Defossilization Targets?

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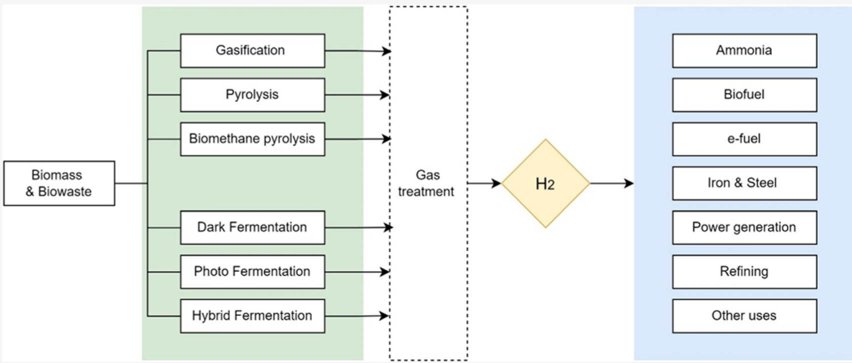

ABSTRACT: This study investigates the potential role of hydrogen production from biomass in the EU hydrogen objectives. With the EU aiming to produce 10 million tons of renewable hydrogen by 2030 and significantly scaling this production by 2050, diverse hydrogen production pathways must be explored. Our research focuses on assessing whether biomass-derived hydrogen can serve as a viable and substantial component of the hydrogen production mix alongside and complementing established methods such as electrolysis powered by renewable electricity. Through a comprehensive literature review, the main hydrogen production pathways from biomass have been assessed, including thermochemical and biological methods, with an emphasis on hydrogen yield, production costs, and technology readiness levels (TRLs). The work also considers the availability of biomass resources and potential production scenarios for 2030 and 2050. Our findings suggest that biomass-derived hydrogen can meaningfully contribute to the defossilization of the hydrogen sector, particularly in the midterm scenario for 2030. The analysis suggests that biomass has the potential to contribute a substantial share of the EU's 2030 hydrogen target, ranging from under 0.1 Mt to over 16 Mt per year. Biomass-derived hydrogen offers additional flexibility and security of supply in the transition to a sustainable hydrogen economy, other than the possibility to benefit from negative emissions in some cases and added value from the coproduction of defossilized materials and chemicals, relying on domestic resources available in Europe.

1. INTRODUCTION

Hydrogen is an industrial commodity that is largely produced and utilized on a global scale. Traditionally, hydrogen production has relied heavily on fossil-fuel-based processes, particularly natural gas reforming, which account for approximately 95% of the world's hydrogen supply. In absolute terms, in 2022, around 95 million tons of hydrogen were consumed globally, with nearly 30% in China and only 8–9% in Europe.[1]

The main demand segment for hydrogen is refining, which accounts for 33% of the total, followed by ammonia production (27%), methanol production (11%), and direct iron reduction (3%). In 2022, an oil refinery consumed more than 41 million tons of hydrogen, surpassing the 2018 record. Around 80% of the hydrogen used is produced directly on site, with 55% generated from dedicated plants and the rest obtained as byproduct of refinery process. The most widespread use of hydrogen in refining routes is related to hydro-treatment and hydrocracking processes, where the first process removes impurities from crude oil, mainly sulfur (sometimes referred to

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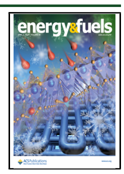

as desulfurization), and the other one upgrades residual heavy oils into high-value products.[1] The chemical sector has two of its industries in the second and third place in the hydrogen consumption ranking (i.e., ammonia and methanol production). In 2019, ammonia production consumed about 31 Mt of hydrogen, followed by methanol with 12 Mt. Ammonia is mainly used for producing fertilizers (about 80%) such as urea and ammonium nitrate[2] through the Haber Bosch process. The demand for fertilizers is expected to grow in the coming decades, driven by demographic and economic growth in some countries, leading to a consequent increase in the hydrogen demand. Methanol, on the other hand, is used in several industrial applications, such as the production of various solvents, fuels (methanol-to-gasoline), or other chemicals (methanol-to-olefins or methanol-to-aromatics), beyond its use in transport.[3] Another significant use of hydrogen is in steel production: the steelmaking process is mainly coal-based, with fossil coke utilized in the BF-BOF (Blast Furnace-Basic Oxygen Furnace) process both for iron oxide reduction and heat generation, leading to the production of 1.6 to 3.2 tons of CO_2 per ton of crude steel. One alternative method for reducing iron oxides is direct reduction of iron (DRI), which uses a mixture of hydrogen and carbon monoxide. This technology covers only a small share of the steel market, about 7% of global production, but ranks fourth when it comes to the use of hydrogen (4 Mt in 2019). Hydrogen production in this case is done primarily on-site, utilizing the natural gas reforming process. In addition to traditional uses of hydrogen, new potential applications are emerging, such as the hydrogen DRI process for producing green steel.[4,5] Other applications include the production of hydrogen-based fuels, such as ammonia,[6] methanol, and other hydrocarbons,[7] the upgrading of biofuels[8,9] and their use in energy storage.

Hydrogen production is currently dominated by fossil-based technologies like steam methane reforming (SMR) and coal gasification (CG), with a share of production, respectively, of 64 and 21%. Another significant fraction of the total hydrogen is produced as a byproduct of different processes related to refineries. Finally, low-carbon technologies, including water electrolysis and fossil-based production with carbon capture and storage (CCS), cover a share of less than 1% in the global production.[1] Considering the pivotal role assumed for hydrogen in the energy transition challenge, strong acceleration is needed to adopt more sustainable hydrogen production pathways.

Electrolysis's electrical consumption ranges between 44 and 56 kWh/kg H_2,[10,11] and when this electricity comes from renewable or nuclear energy, it presents an important pathway to CO_2-free hydrogen production. Despite this, some challenges related to this technology remain. Its scale-up to the industrial level is constrained by high capital costs, dependency on critical materials, often imported from non-EU countries, and the limited availability of renewable electricity. Even if renewable capacity is increasing in almost all of the countries' energy mix, it remains insufficient to meet the growing hydrogen demand, especially if considering the competition with other sectors such as power generation, transportation, and heating. Expanding the renewable infrastructure is mandatory to meet European green hydrogen targets,[12] and it should happen faster than it was in the past.

The European Union's "European Hydrogen Strategy" outlines ambitious goals: achieving 1 million tonnes of green hydrogen production by 2024 and increasing this target 10-fold by 2030. Achieving these targets necessitates the installation of 6 GW of electrolyzer capacity by 2024, scaled up to 40 GW by 2030. The latest IEA hydrogen report reveals a significant delay in targets, with global electrolysis hydrogen production reaching only 100 kt in 2023. Projections for 2030 estimate European production at nearly 8 Mt, most of which is still in early development stages.[13] Hydrogen Europe's 2024 report revises these figures downward, forecasting a green hydrogen supply from electrolysis of only 1.7 Mt under the current trajectory and up to 3 Mt in an accelerated adoption scenario, both well below the 2030 European target.[14] Beyond technological challenges, Europe must address the need for extensive upgrades to its electricity transmission grid, which is currently poorly equipped in many regions to handle the increased loads required for large-scale electrolysis plants.

To meet these ambitious targets, exploring alternative and complementary hydrogen production pathways is essential. CCS technologies, which can integrate with existing fossil-fuel-based infrastructure, represent a transitional solution but face scalability challenges in the short to medium term.[15] Biobased hydrogen production, utilizing biomass and biowaste as renewable feedstocks, is another promising alternative. These processes offer the potential for net-zero or even negative CO_2 emissions, as demonstrated by extensive literature studies on the thermochemical and biological conversion of organic materials to hydrogen.

Recent studies have highlighted the potential of biobased technologies. Nguyen et al.[16] reviewed advances in hydrogen production via biomass pyrolysis and gasification. Challenges such as tar removal and catalyst deactivation, were identified as key barriers. Arregi et al.[17] and Pandey[18] et al. provided comprehensive reviews of the state-of-the-art for thermochemical conversion technologies, while Shahabuddin et al.[19] and Obiora et al.[20] conducted techno-economic analyses. Biological conversion pathways, such as dark and photo fermentation, have also been extensively reviewed. Goren et al.[21] identified hybrid fermentation as a promising approach, achieving high hydrogen yields, compared with other biological processes. Comparative analyses, such as those by Lepage et al.[22] and Nikolaidis et al.,[23] examined both thermochemical and biological technologies, providing insights into pathways for competitive biohydrogen production.

Despite this extensive body of research, biobased hydrogen technologies remain underrepresented in global hydrogen strategies. Implementation studies and analyses of their potential impact on hydrogen production scenarios are limited. Notably, in 2022 Rosa et al.[24] evaluated hydrogen production from sustainable biomass integrated with CCS, demonstrating a potential annual production of 12.5 million tonnes of hydrogen (exceeding the EU 2030 target of 10 million tonnes) and simultaneous removal of 133 million tonnes of CO_2 from the atmosphere. However, this analysis was restricted to biomethane steam reforming, underscoring the need for a broader assessment of technologies. In alignment with these considerations, the European Innovation Council has recently launched a pathfinder challenge[25] with the vision to pursue green H_2 generation pathways and technologies that rely on domestic resources and non critical materials, prioritize the uses of hydrogen where it most matters, and capture system-level benefits with the coproduction of multiple green co-products. The portfolio of retained projects focuses on the potentials of new biological, chemical, and physical routes for green H_2 production, which could also facilitate the

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implementation of the circular economy principles, possibly including the co-production of decarbonized chemicals. The specific target was to support the development of innovative technologies and supply chains for green H_2 production, including both centralized and/or on-demand generation (i.e., at the premises of the end users and for onsite consumption).

In alignment with the activities of strategic relevance for the EU identified in the action plan of this EIC portfolio, the scope of this work is to assess the potential of sustainable hydrogen production from biomass feedstock within the European context. This review provides a comprehensive overview of the most promising biomass-to-hydrogen technologies and critically analyzes their capacity to contribute to future hydrogen demand scenarios for 2030 and 2050. Through this analysis, we aim to highlight the role that biobased hydrogen can play in supporting European energy transition, demonstrating how these technologies can complement existing methods to build a more diversified and resilient hydrogen economy.

The present study aims to evaluate the potential for hydrogen production in Europe across all available technologies, taking into account both thermochemical and biological processes. By comparing these results with updated EU objectives and other hydrogen demand forecasts, this work seeks to provide a comprehensive outlook on the role of biobased and alternative pathways in meeting future hydrogen targets. The research question can therefore be reformulated as follows:

What Is the European Potential of Green Hydrogen in 2030 and 2050, Considering the Availability of Biomass across Different Scenarios? The methodology adopted includes the following main steps:

- Identification of the biomass availability for energy purposes in Europe by 2030 and 2050;
- Assessment of hydrogen yield expressed as $g_{H2}/kg_{biomass}$ for different routes (both thermochemical and biological), through an extensive literature review;
- Estimation of the amount of the potential green hydrogen, and its comparison with European targets.

2. MATERIALS AND METHODS

2.1. Biomass Potential Assessment. To estimate the future biomass potential for energy purposes, data from multiple sources were analyzed and compared. Throughout this study, terms such as "biomass potential" and "sustainable biomass" are frequently used. For clarity, "biomass potential" refers to the maximum estimated quantity of biomass available at a given time. "Sustainable biomass", on the other hand, describes biomass availability calculated under different assumptions about land use, agricultural practices, and the designation of protected areas. Furthermore, renewable energy produced from biomass feedstocks following the implementation of indirect land use change (ILUC) mitigation measures has the potential to reduce dependence on fossil fuels without competing with the food value chain. According to the Renewable Energy Directive II, low ILUC-risk biomass feedstocks are produced following the implementation of sustainable agricultural practices, i.e., (i) yield increases through improved agricultural practices or (ii) cultivation on land not previously used for crop production, e.g., unused, abandoned or severely degraded land or (iii) combination of cover crop rotations with biomass feedstock production.[26] These measures are also fundamental for returning organic carbon to the soil and promoting soil health as key elements for sustainable bioeconomy supply chains that also ensure the production of sustainable fuels.

To address these assumptions, three mobilization scenarios (LOW, MEDIUM, and HIGH) were identified in the literature. These scenarios encompass varying levels of resource mobilization based on the aforementioned factors. For detailed definitions and methodologies associated with these scenarios, the reader is referred to the respective studies.

The first source of data was the ENSPRESO database, an EU-28 open-access resource that compiles potential estimates for wind, solar, and biomass energy.[27] For biomass, the ENSPRESO database estimated potentials ranging between 199 and 434 Mtoe (approximately 497 and 1082 Mtdm) for 2030 and between 195 and 497 Mtoe (approximately 487 and 1242 Mtdm) for 2050. A second key data source was the European Commission's 2017 study, "Research and Innovation Perspective of the Mid- and Long-Term Potential of Advanced Biofuels in Europe".[8] This study estimated biomass potentials ranging from 191 to 264 Mtoe (about 478 and 660 Mtdm) for 2030 and from 224 to 300 Mtoe (approximately 560 and 750 Mtdm) for 2050. More recently, the European Commission's 2024 report, "Development of Outlook for the Necessary Means to Build Industrial Capacity for Drop-in Advanced Biofuels", hereafter called "RTD 2024",[28] provided updated estimates. This report projected biomass potentials for 2030 between 310 and 836 Mtdm, and for 2050 between 299 and 894 Mtdm.

For this analysis, the 2024 report was chosen as the primary reference due to its comprehensive and updated values. The report also provided a detailed breakdown of biomass potential by feedstock type, including categories such as straw, manure, and forestry residues. This characterization allowed for the association of specific feedstock types with their most suitable conversion processes, both thermochemical and biological.

To calculate the hydrogen production potential, the conversion efficiencies of these processes were applied to the biomass feedstock data. The results were adjusted to account for competition with other energy applications by incorporating a reduction factor ranging from 5 to 20%. This adjustment reflects the proportion of biomass likely to be diverted to alternative uses. By applying this reduction factor to biomass availability, a range of hydrogen production potentials was derived, corresponding to different scenarios of resource allocation.

This approach enabled the integration of feedstock-specific conversion efficiencies alongside realistic assumptions about biomass competition to generate robust estimates for hydrogen production potential under varying mobilization and allocation conditions.

The following equation summarizes the calculation described for hydrogen production potential, used for all of the routes under investigation:

$$\text{Hydrogen production}\left(\frac{Mt}{y}\right) = \text{hydrogen yield}\left(\frac{g_{H_2}}{kg_{\text{biomass}}}\right) \times \frac{1}{1000} \times \sum_{i=1}^{N} \text{available biomass}_i \left(\frac{Mt_{\text{dm}}}{y}\right) \times \text{biomass utilization\%}$$

2.2. Hydrogen Demand in Europe. The hydrogen demand projections were derived for the 2030 and 2050 scenarios, using the "Scenarios for future hydrogen demand" database from the *European Hydrogen Observatory*. This database contains data from various studies conducted by different organizations in Europe. The forecasts were derived using a large number of assumptions, which leads to a wide range of variation in the results, especially for 2040 and 2050. The data set divides the EU demand into four main sectors: industry, transports, buildings, and electricity. All of these end-use sectors were considered for this study regardless of the technological or economic feasibility to match that demand segment with hydrogen, in order to evaluate the entire spectrum of hydrogen end uses and the potential role of biomass. Further discussion on the appropriate application of hydrogen will also be also provided.

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2.3. Hydrogen Production Yield from Biobased Processes. A literature review was conducted to evaluate the potential for the production of hydrogen from organic streams via various pathways. The primary performance indicator used for comparing technologies was hydrogen yield, expressed as grams of hydrogen per kilogram of dry feedstock (g of H_2/kg biomass). Where available, the data in this unit were directly extracted from the literature. For studies presenting results in different units, such as Nm^3 H_2/kg biomass, additional data were utilized to convert these values into mass yield. For biological processes, results were often reported using different units, and conversion to the desired unit was not always feasible due to insufficient data. In such cases, those studies were excluded from the analysis. Among the pathways considered, biomethane pyrolysis was the only process starting from an intermediate product rather than biomass directly. To ensure a fair comparison across technologies, this pathway was assumed to include a prior anaerobic digestion stage for biomethane production, with a conversion factor of 0.31 kg CH_4/kg biomass based on literature values.[24] Additional indicators, including carbon intensity, TRL, and hydrogen production cost, were sourced from studies separate from those used to assess the hydrogen yield. This approach was necessitated by the early-stage nature of much of the reviewed work, which often lacked commercial or economic data.

2.4. Biomass-to-Hydrogen Processes Investigated. Hydrogen production from biomass can be categorized into two primary processes: thermochemical and biological. Thermochemical processes use thermal energy to break down biomass, decomposing complex hydrocarbons into smaller molecules, such as hydrogen, carbon monoxide, and methane. This category includes gasification, pyrolysis, and biomethane decomposition. On the other hand, biological processes rely on enzymes and bacteria to convert organic matter under specific conditions, generating useful gases such as hydrogen. The value of biomass or biowaste conversion to hydrogen lies in the valorization of waste materials for the coproduction of chemicals, materials, and other compounds where carbon can be long-term stored, offering further revenues to improve the process profitability, and at the same time increasing the CO_2 net sequestration balances.

2.4.1. Gasification. Biomass gasification is a viable process for hydrogen-rich gas from organic materials, such as lignocellulosic biomass and dry biobased waste. The process converts these materials into syngas, where the hydrogen content typically ranges between 30 and 50 vol %. To enhance the hydrogen concentration and achieve more efficient conversion, optimizing operational parameters and plant configurations is essential. Key factors include the selection of an appropriate gasification agent, such as steam or pure oxygen, which can significantly increase the hydrogen yield. Additionally, the use of catalyst materials, the implementation of reactors with superior heat exchange properties (such as fluidized bed reactors), and the adjustment of the steam-to-biomass ratio are crucial elements that can further improve the efficiency of hydrogen production.

The first step for hydrogen production is gasification, which can be classified according to the gasification agent, heat source, and reactor configuration. This step is followed by the cleaning stage, which is essential for the separation of particulates and contaminants such as sulfur, nitrogen, and chloride compounds as well as tars. Typically, cyclones and filters are used to remove bulk particles, while scrubbing is required for dust. The gas removal stage addresses sulfur compounds and CO_2. If the tar content is high, then a reforming stage with additional scrubbing is necessary. Furthermore, in the gas conditioning stage, the hydrogen ratio is adjusted by water−gas shift (WGS) reactions. If hydrogen is the main output, WGS is crucial for enhancing the H_2/CO ratio and maximizing yield. Furthermore, after WGS, the hydrogen in the syngas usually ranges between 60 and 70 vol %.[29] Finally, a purification stage is necessary for applications that require pure hydrogen. The most common method is pressure swing adsorption, followed by technologies, such as membrane separation. At the end of the process, the hydrogen purity can be very high, about 99.9%.

Regarding operational conditions, gasification typically takes place at a temperature between 700 and 1200 °C, using a gasifying agent, that can be air, pure oxygen, steam, or a mixture of them.[17] The choice of the gasifying agent is very important as it affects both the costs and the performances of the process. In air gasification, the high nitrogen content in the feed results in the production of a highly diluted syngas, with nitrogen concentrations reaching up to 45−55 vol %. This significant presence of nitrogen not only complicates the subsequent separation of hydrogen but also leads to the generation of syngas with a low calorific value, typically ranging from 4 to 7 MJ/kg. When pure oxygen is used, the calorific value of the syngas increases significantly (10−15 MJ/kg), along with the percentage of hydrogen in the gas mixture. The drawback associated with this solution is the cost required for separating oxygen from the air. Instead, with the use of steam, ensuring a quite high calorific value (10−20 MJ/kg) and a high hydrogen percentage in the syngas, the cost is significantly lower than that in the pure oxygen case. The hydrogen produced in the latter case does not only come from the treated biomass but also from the additional contribution provided by the steam used as a gasifying agent.[30,31] This is in fact the preferred solution for the production of hydrogen via biomass gasification.

Gao et al.[32] studied a fixed bed gasifier with further reforming on a porous ceramic material. The study highlighted an increase of the hydrogen yield with the steam/biomass (S/B) fraction, reaching values close to 52 gH_2/kg biomass for values of S/B ratios of 2.5. Instead, Lv et al.[33] carried out several laboratory experiments on autothermal downdraft gasification, using char as a catalyst and air or a mixture of oxygen and steam as gasifying agents. The results showed that the use of oxygen and steam significantly increased the hydrogen content in the output gases, reaching a maximum value of 45.16 gH_2/kg of biomass.

Temperature also represents a fundamental parameter for studying the behavior of the gasification process, and there are many studies examining the effects of its variation on the distribution of final products. Generally, it has been observed that as temperature increases, the hydrogen content in the syngas also increases.[17,18] The reasons for this positive effect are manifold. First, according to Le Chatelier's principle, an increase in temperature favors endothermic reactions, which represent a significant portion of the gasification process reactions. Second, temperature promotes the breaking of heavy molecules, increasing the production of final products such as hydrogen and CO.[34] Consequently, this leads to a reduced tar content at high temperatures. Lastly, high temperatures also enhance mass and heat transfer processes, improving the overall efficiency of the gasification,[35] although this also leads to problems of wear of the materials, due to the more aggressive conditions, and consequent increase in costs.

Regarding reactor configurations for biomass gasification, three main categories are commonly adopted: fixed bed, fluidized bed, and entrained flow reactors.[16,36] The impact of these configurations on the hydrogen yield is complex and influenced by various factors, including scale, biomass composition, and operating conditions. However, based on reviews of experimental studies,[37−41] fluidized bed reactors have emerged as the most effective option for hydrogen production. This is primarily due to their ability to achieve high hydrogen yields while maintaining low tar levels, which is a significant advantage in the gasification process.[17] Within the fluidized bed category, the dual fluidized bed configuration is particularly noteworthy.[17,42] This design addresses one of the key challenges in biomass gasification: the need for an efficient heat supply. By utilizing combustion of the produced char and a portion of the gas, the dual fluidized bed effectively overcomes heat supply issues, thereby enhancing the overall efficiency of hydrogen production. In cases where a CCS unit is integrated into the process, studies have shown that it may be possible to produce hydrogen with a negative GHG footprint.[43]

2.4.2. Pyrolysis. Pyrolysis is a thermochemical process in which biomass is converted into three components in the complete absence of external oxygen: a noncondensable gas (pyrogas), a liquid (bio-oil), and a solid (biochar). The reaction is divided into three stages: drying, with the evaporation of the moisture content of the biomass at a temperature below 200 °C; primary pyrolysis, in which the biomass undergoes devolatilization reaction and the main components (cellulose, hemicellulose and lignin) start to decompose;[44] and the secondary pyrolysis, where the heavy compounds are broken down into lighter molecules (H_2, CO, CH_4, and CO_2).[45,46] The distribution of the outputs depends on the type of pyrolysis, which can be categorized into slow, fast, and flash pyrolysis. Slow pyrolysis primarily produces solid and gaseous phases, with residence times in the order of minutes, temperatures between 400 and 500 °C, and relatively low heating rates (0.1−1 °C/s).[18] This process has traditionally been employed to produce char, also known as charcoal, a material characterized by its high carbon content (fixed carbon ranging from 80 to 87%) and significant energy density (with a higher heating value between 30 and 32 MJ/kg).[47,48] Despite the larger fraction of the gaseous phase, slow pyrolysis shows a reduced hydrogen production, which increases with higher temperatures and heating rates.[49,50] Evaluating the effect of temperature on the distribution of the three phases, it was found that the concentration of hydrogen in the syngas increases as the temperature rises (from 7% at 773 K to 28.8% at 953 K).[51] Furthermore, the temperature promotes the breakdown of heavy molecules in tar, thus favoring the formation of lighter molecules such as H_2, CO, and CO_2,[52,53] together with the decomposition of CH_4 into hydrogen and carbon. The equations governing hydrogen production, in a temperature range between 600 and 900 °C, during the slow pyrolysis process are as follows:[51]

$$C_nH_m + nH_2O \leftrightarrow nCO + \left(n + \frac{m}{2}\right)H_2 \quad (1)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad (3)$$

One possible solution to increase the gas fraction in slow pyrolysis is to catalyze the cracking reactions of heavier molecules at the same reaction temperature[54] utilizing dedicated catalysts. Fast pyrolysis is mainly used to produce bio-oil, which can account for up to 75% by weight.[55] The high yield of the liquid phase is due to the short residence time of the biomass in the reactor, typically just a few seconds, with temperatures around 500−600 °C and heating rates between 10 and 200 °C/s. Beyond a certain time and at temperatures above 600 °C, the yield of bio-oil decreases due to secondary reactions, which favor the formation of the gaseous phase.[56] Besides the primary objectives of producing carbonaceous material through slow pyrolysis and bio-oil via fast pyrolysis, the process is also recognized as an effective method for hydrogen production from biomass.[51] The produced bio-oil can be further upgraded into hydrogen through a reforming stage, taking the name of two-stage pyrolysis-catalytic reforming. During the process, biomass is initially converted into heavy hydrocarbons, which are present in the condensable phase, and then converted in the steam reforming stage.[57,58] The separation of the two processes offers various advantages over biomass gasification, allowing for the separate and optimized control of operational parameters in different zones.[17] Additionally, lower temperatures in the reforming stage can help avoid sintering phenomena that cause catalyst deactivation.[59,60] Regarding the catalyst, several studies have evaluated Ni-based catalysts, as they are widely used in hydrocarbon reforming processes.[61] Further advantages over direct biomass gasification include that the latter aims to produce syngas, while the reforming stage in the two-stage process aims to produce hydrogen. Moreover, the reforming process allows for the decomposition of all heavy hydrocarbon molecules, resulting in an output gas phase almost tar-free.[62] The reforming of bio-oil can be done in-line, immediately downstream of the pyrolysis reactor, avoiding the need to condense and separate it from other products, or it can be collected and transported to another location for centralized reforming.

2.4.3. Biomethane Pyrolysis. In this process, also known as methane decomposition, methane molecules are converted into hydrogen and solid carbon at temperatures that depend on the type of the process. The minimum temperature at which the reaction occurs is 500 °C if a catalyst is used, and 700 °C otherwise.[63,64] These temperatures must be further increased to achieve good conversion rates, typically in the range of 800−1000 °C.[65]

$$CH_4 \leftrightarrow 2H_2 + C\Delta H_r^0 = 74.91\ \text{kJ}\cdot\text{mol}^{-1} \quad (4)$$

The equation only describes the main reaction occurring in the process; however, small fractions of hydrocarbons and other compounds are also produced.[66,67] Taking this into account, we must consider additional separation and purification stages to obtain pure hydrogen. Based on a mass balance from the equation, solid carbon is the main product of the reaction: 750 kg of theoretical produced solid carbon for every ton of CH_4, compared to 250 kg of hydrogen. Therefore, it is essential to economically valorize the carbon to make the process sustainable.[68] The methane pyrolysis process can be carried out through three main pathways: thermal decomposition, catalytic decomposition, and plasma decomposition.

In the thermal decomposition of biomethane, higher reaction temperatures are required, varying depending on the reactor configuration, but generally well above 1000 °C.[68] A first process was developed from BASF, with a fluidized bed reactor in which the bead was made of carbon granules. In this case, the heating mechanism consisted of two stages: an initial heat recovery from the exiting carbon granules, followed by the primary heating through electrical heating using electrodes inserted into the reactor, reaching up to 1400 °C. Another configuration utilized liquid metal as a heat transfer medium within a bubble column reactor, achieving temperatures of approximately 1200 °C and methane conversion rates of up to 78%.[69]

In plasma decomposition, the gas is heated to very high temperatures (1000−3500 °C) by electrically powered plasma torches. One advantage of this technology is the potential to generate higher quality carbon compared to other methods, but it remains a particularly energy-intensive process.[70,71]

The last type of process uses a catalyst to reduce the necessary process temperature.[72,73] Catalysts used include those based on Fe,[74] Ni,[75] metal salts,[71] or carbon.[75] The issue with catalysts is that the carbon produced tends to deposit on them during the decomposition process, leading to deactivation. Therefore, catalyst recovery processes are necessary to carry out the regeneration of the catalysts, but since this is a complex process, they sometimes fail to fully recover the catalyst. A potential solution to some of these challenges could be the use of carbon-based catalysts, which exhibit slower deactivation and offer a more cost-effective alternative compared to metallic catalysts.[74,76]

2.4.4. Dark Fermentation. In this process, hydrogen is obtained by converting waste materials, such as agricultural residues, food scraps, or wastewater. The characteristic reaction is as follows:

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 4H_2 + 2CO_2 + 2CH_3COOH \qquad \Delta G^{\circ} = -206\ \text{kJ} \quad (5)$$

Stoichiometrically, the maximum conversion is 4 mol of hydrogen per mole of glucose. The actual yield is lower than this value because part of the substrate is used for the growth of microorganisms and the production of volatile fatty acids. The bacteria used in this case are anaerobic, such as *Enterobacter sp.*, *Bacillus sp.*, and *Clostridium*.[77] Depending on the type of bacteria used, different hydrogen yields can be achieved, varying the type and amount of fatty acids produced.[78] Additionally, combining different types of bacteria can result in higher hydrogen production than single cultures. However, applications that mix different bacterial cultures can also introduce hydrogen-consuming microorganisms, such as methanogens, which lower the process yield.[79] Other factors influencing hydrogen production include substrate concentration, temperature, and pH. Higher substrate concentrations result in lower hydrogen yields due to thermodynamic limitations.[80] Eker et al.[81] conducted experiments using glucose as a substrate and observed a decrease in hydrogen yield at concentrations above 18.9 g/L. Regarding pH, values below 5 inhibit hydrogenase activity, halting hydrogen production.[82] Ozyurt et al. showed that maintaining a pH of 6 increased hydrogen production by 18.4%.[83] The operational temperature can vary depending on whether mesophilic (25−40 °C), thermophilic (40−65 °C), or hyperthermophilic (above 80 °C) conditions are used. Generally,

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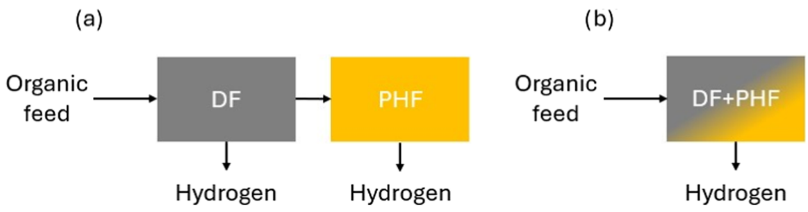

Figure 1. Hybrid fermentation processes: (a) sequential execution of dark and photo fermentation in separated reactors; (b) integration of both processes into a single step.

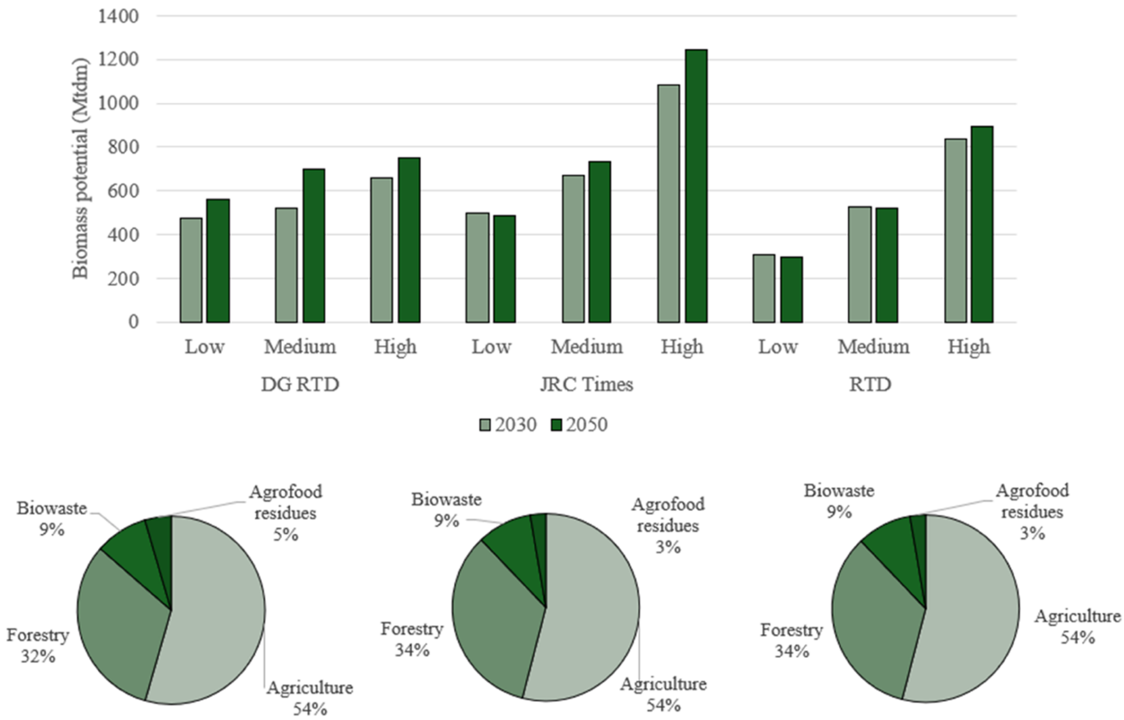

Figure 2. Biomass potential in EU-27 for 2030 and 2050, in three different studies: DG RTD, JRC Times, and RTD. The pie charts represent the categorization of biomass for the RTD study, respectively, for LOW, MEDIUM, and HIGH scenarios.

various studies have shown that within characteristic ranges, increasing the temperature increases hydrogen production

2.4.5. Photo Fermentation. In photo fermentation, hydrogen is produced by bacteria such as *Rhodobacter, Rhodopseudomonas*, or *Rhodospirillum*.[84] These bacteria change their behavior depending on the conditions to which they are exposed, such as irradiation, carbon sources, and oxygen presence. Depending on these conditions, they can grow photoautotrophically, photoheterotrophically, or chemoautotrophically. In photoheterotrophic conditions, sunlight is used as an energy source, while organic compounds are used as carbon sources for the organism's growth and hydrogen production. This process is catalyzed by two enzymes: nitrogenase and hydrogenase. The substrate is oxidized into CO_2, protons, and electrons. The electrons are then transferred to nitrogenase. Simultaneously, Adenosine triphosphate (ATP) is formed by the Photosystem I (PSI) system, which utilizes energy from solar irradiation. Finally, the enzyme nitrogenase reduces protons, generating hydrogen. Another side process, uptake hydrogenase, consumes some of the produced hydrogen to form protons and electrons again. The bacteria used in this process can adapt to a wide range of substrates, but their selection remains a crucial parameter for process efficiency.[85] Carbon sources include carbohydrates such as glucose, fructose, and sucrose, or acids like acetic, lactic, butyric acids, aromatic compounds, and alcohols.[86,87] Studies have shown that not all of these components are suitable for use in photo fermentation; for example, simple sugars like glucose and fructose are less efficient than acids.[88] Light is a fundamental element for this process, and characteristics such as the source, intensity, and distribution can greatly influence system efficiency. The energy from light is necessary for ATP formation, which is key for nitrogenase activity and the resulting hydrogen production.[89] Illumination can be external or internal to the reactor using natural or artificial light. External illumination is hindered by low penetration due to shading effects.[90] Pilot configurations of such plants are typically placed outdoors to directly utilize sunlight. Despite the low costs of these plants, issues such as shading, contamination from external agents, and light fluctuation arise. Conversely, using bioreactors with artificial lighting overcomes most of these challenges but incurs higher operational costs.[89]

2.4.6. Hybrid System. Higher hydrogen production yields and lower light energy requirements can be achieved by using hybrid systems. These systems utilize both nonphotosynthetic (anaerobic) and photosynthetic bacteria. Anaerobic bacteria can digest a variety of carbohydrates to produce hydrogen in the absence of light and the resulting organic acids can then be used by photosynthetic bacteria to produce additional hydrogen.[91] This combined process of dark and photo fermentation is known as sequential dark/photo fermentation. Integration can be achieved through two configurations: sequentially executing the two processes, or combining them into a single process (Figure 1).[92] Theoretically, this approach can yield up to 12 mol of hydrogen per mole of glucose, although the highest practical yield reported is 7.1 mol H_2 per mole of glucose.[93] Key factors influencing hydrogen yield include temperature, which enhances H_2 production as it rises, and pH levels, which should be between 4.5 and 6.5 for fermentative bacteria and above 7 for photosynthetic bacteria.[94]

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3. RESULTS AND DISCUSSION

3.1. Biomass Availability Potential. Figure 2 presents findings from reports on biomass potential in Europe. The histogram illustrates the projected biomass available for energy purposes in Europe for 2030 and 2050, based on three studies considered. The RTD scenario was selected as the reference scenario for the calculations in this work. The pie chart displays the distribution of potential biomass from the RTD scenario, divided into four main categories corresponding to the LOW, MEDIUM, and HIGH scenarios, starting from the left. Tables 1 and 2 provide a further breakdown of these biomass categories, along with their respective quantities and technological allocations.

Table 1. Definition of Biomass Used for Thermochemical and Biological Processes[a]

Biomass 2030 potential (Mtdm)	LOW	MEDIUM	HIGH	conversion technology
Total	310.6	523.9	836.6	
Straw	66.8	148.4	259.1	thermochemical
Prunnings & damaged crops	5	9.4	13.6	thermochemical
Manure & sewage sludge	110.4	132.6	174.5	biological
Agroprocessing residues	3.4	5.8	9.1	biological
Lignocrops abandoned degraded	2.8	5.9	10.1	thermochemical
Lignocrops inter and cover cropping	0.7	3	8	thermochemical
Oil crops abandoned, degraded, intercropping	0.2	0.7	1.6	
Stemwood	32.7	92.1	202.6	thermochemical
Primary forestry residues	37.4	42.9	42.9	thermochemical
Secondary forest residues	24.9	42	59.1	thermochemical
Biowastes	23.8	36.6	47.9	bio./thermochemical
UCO, brown grease, animal fat	2.3	4.5	8	

[a]Data from RTD 2030 projection.

3.2. Technological Comparison of Biobased Processes. The proposed methodology evaluates hydrogen yield across various technologies based on the literature data. Figure 3 shows a box plot of the hydrogen yield (expressed in $g_{H2}/kg_{biomass}$) with the median line in yellow, the interquartile range in green (encompassing 50% of the values), and the overall range.

Thermochemical processes show higher biomass conversion compared to biological processes, with an average hydrogen yield of 53.96 and 20.36 $g_{H2}/kg_{biomass}$, respectively. Among the thermochemical processes, pyrolysis showed better results, with an average yield of 65.44 $g_{H2}/kg_{biomass}$ and a maximum yield of 148 $g_{H2}/kg_{biomass}$. These promising results are due to the configuration of most of the study analyzed, which integrates a step of in-line steam reforming into the process, in order to convert the oil phase. It is important to highlight that most of the gasification studies were at a laboratory scale, and often, they omitted the water gas shift stage after the gasification, limiting the final hydrogen production. A study from Lepage et al.[22] reported higher conversion results for this technology, up to 190 $g_{H2}/kg_{biomass}$.

Table 2. Definition of Biomass Utilized for Thermochemical and Biological Processes[a]

Biomass 2050 potential (Mtdm)	LOW	MEDIUM	HIGH	Conversion technology
RTD	299.5	525.9	894.6	
Straw	51.6	128.8	241.9	thermochemical
Prunnings & damaged crops	4.5	9.2	13.4	thermochemical
Manure & sewage sludge	102.8	124.4	163.7	biological
Agroprocessing residues	3.2	5.5	10.2	biological
Lignocrops abandoned degraded	17.8	36.8	74.7	thermochemical
Lignocrops inter and cover cropping	1.4	6.4	19	thermochemical
Oil crops abandoned, degraded, intercropping	0.7	2.1	5.3	/
Stemwood	25.4	77	196.9	thermochemical
Primary forestry residues	36.8	42.7	42.7	thermochemical
Secondary forest residues	26.4	44.8	63.2	thermochemical
Biowastes	20.4	36	48.6	bio./thermochemical
UCO, brown grease, animal fat	8.5	12.2	15.2	/

[a]Data are from the RTD 2050 projection.

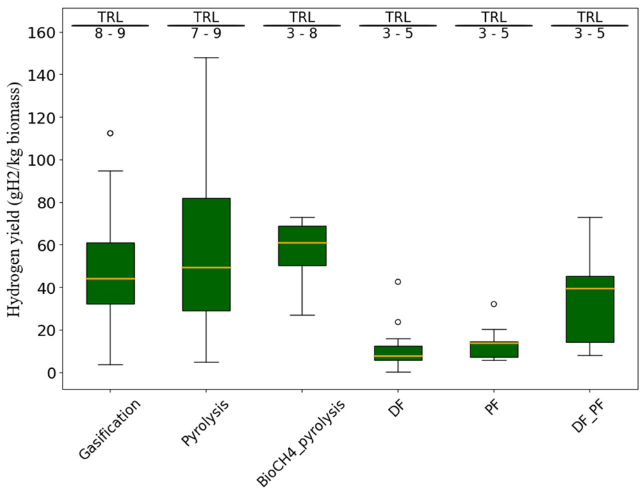

Figure 3. Hydrogen production efficiency (gH_2/kg biomass) for different thermochemical and biological conversions of biomass. The yellow line represents the median data elaborated from the literature.[25,30,32,33,37,40,62,95−]

It is clear from the wide range of values, mainly for thermochemical pathways, how the final hydrogen yield is strongly influenced by the operational parameters.

Among biological processes, the hybrid configuration of dark and photo fermentation reached the highest conversion value, with an average of 37.27 $g_{H2}/kg_{biomass}$.

From an energy efficiency perspective, thermochemical processes outperform biological methods. Buffi et al.[131] reported energy efficiencies of 0.43−0.7 for wood gasification, compared to 0.01−0.1 for photo fermentation and 0.1−0.25 for dark fermentation. Integrated processes of dark and photo fermentation show slightly higher efficiencies (0.27). Methodological differences in efficiency calculations can affect results; some studies even report negative efficiencies due to

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nonrenewable energy offsets.[132] Nikolaidis et al.[23] reported efficiencies of 0.35−0.5 for biomass pyrolysis, 0.01 for photo fermentation, and 0.6−0.8 for gasification. Comparatively, Ptasinski's analysis found dry biomass gasification efficiencies (0.66−0.79) comparable to those of steam methane reforming (0.78). Wet feedstocks yield lower efficiencies, with gasification at 0.36−0.4 and integrated fermentation at 0.3−0.36.[133] Biological processes, while operating under milder conditions and requiring less energy input, exhibit lower conversion rates and necessitate considerable energy for plant operation, resulting in a reduced overall efficiency.

The maturity of the different technologies is assessed by the TRL. High-maturity technologies such as water electrolysis show a TRL of 9 (for PEM and AEM systems). Biobased processes present a wide range of TRLs. Gasification is the most developed technology, showing a TRL between 8 and 9, depending on the configuration.[22,134] Pyrolysis shows lower TRL values, especially for the intermediate products treatment (e.g., bio-oil reforming), with a range between 6 and 9, also in this case strongly influenced by the configuration adopted.[135,136] Biomethane pyrolysis's maturity ranges between 3 and 8, including industrial scaled technologies such as plasma pyrolysis (e.g., Kværner and Monolith), but also less mature configurations, like catalytic pyrolysis (e.g., HYPRO and Hazer Group).

Biological processes, with TRLs between 3 and 5, face challenges in optimizing microbial activity and handling feedstock variability.[22,134,137] Nevertheless, their potential for resource recovery and reduced environmental impact provide a compelling incentive for further research and development. Efforts to improve the scalability and efficiency are ongoing. Table 3 summarizes hydrogen yields and TRLs for the processes discussed.

Table 3. Results of the Review of Efficiency Studies Available in the Literature for All of the Hydrogen Production Pathways

technology	TRL	H2 yield ($g_{H2}/kg_{biomass}$)
Gasification	8−9[22,134]	4−113
Pyrolysis	6−9[135,136]	5−148
BioCH4 pyrolysis	3−8[68]	27−73
Dark fermentation (DF)	3−5.[22,134,137]	0.2−42
Photo fermentation (PF)	3−5.[22,134,137]	5.7−32
Hybrid fermentation (DF+PF)	3−5.[22,134,137]	8−72.8

3.3. Potential Role of Biohydrogen in Europe.

Figures 4 and 5 illustrate projections for hydrogen production from biobased processes for 2030 and 2050, respectively, under various scenarios characterized by different levels of mobilization (low, medium, and high) and biomass utilization efficiencies (5, 10, 20, 50, and 100%). These projections are compared against a minimum and maximum expected hydrogen demand, indicated by the shaded regions in the figures.

In Figure 4, the projected hydrogen demand ranges from 3.90 to 28.79 Mt. In the Low scenario, hydrogen production, as represented by the average values (yellow markers), remains significantly below the maximum forecast across all utilization levels. Only in 100% utilization does hydrogen production slightly exceed the maximum forecast, reaching 29.67 Mt. At lower utilization levels (5, 10, 20, and 50%), production remains modest, with averages ranging from 0.6 to 6.7 Mt. The Medium scenario shows a marked increase in hydrogen production. At 100% biomass utilization, production levels approach the maximum forecast, indicating the significant potential for increased biomass mobilization. Although the average production still falls slightly below the maximum forecast, it highlights the importance of mobilization in maximizing biomass resource exploitation. In the High scenario, hydrogen production is maximized, with theoretical biomass utilization potentially yielding nearly 84 Mt of hydrogen, far exceeding the maximum forecast (even with an average production value of 37 Mt).

Figure 5 illustrates the hydrogen production projections for 2050. In this scenario, hydrogen production remains relatively constant with only a slight increase of 7% in the High scenario. However, there is a significant rise in the upper limit of hydrogen demand, which reaches approximately 161 Mt. Across all scenarios, hydrogen production falls well below this demand level.

Figure 6 provides a closer look at hydrogen production for more realistic biomass utilization percentages, between 5 and 20% for 2030. This figure allows for a comparison of the hydrogen yield with the corresponding EU goal for internal hydrogen production by 2030. It is evident that while the average values do not fully meet this goal, there are two cases (Medium 20% and High 20% scenarios) where higher conversion efficiencies surpass the EU target. Although the EU 2030 goal is not fully met in most cases, these results demonstrate the potential role of biobased processes in contributing to hydrogen supply, particularly in the medium term.

3.4. Broader Implications and Barriers for Biobased Green Hydrogen Innovation.

The use of biomass for hydrogen generation offers further advantages, not here captured, based on the possibility to reuse the carbon extracted from the biomass during the conversion process, for many applications (biochar, bioplastics, bulk chemicals, etc.), which can represent the output with the highest added value and remuneration from one side, and offer opportunities for negative emission technologies (when long duration CO_2 sequestration is achieved) or for displacement of environmental harmful industrial production processes. The other great advantage of these biomass-to-hydrogen processes is the possibility to avoid the use of critical or strategic raw materials (which are often needed for state-of-the-art electrolysis technologies), rely on know-how and sectors where Europe presents a technological leadership and excellent research capability, and develop domestic supply chains with important socioeconomic and environmental side effects for rural and forestry development, job creation, reuse of biobased wastes, and safeguard of the environment. A key aspect to maximize all of these advantages of biomass-to-hydrogen routes, fully captured also in the pathfinder challenge on green hydrogen generation proposed by the EIC pathfinder challenge in 2021,[25] is the systems integration of such supply chains and processes, in particular with proper coupling to existing refineries, biorefineries, and industrial biomass processing plants, in order to match the generation with the optimal uses of the final products (hydrogen- and carbon-based materials/chemicals).

Despite that, most of the technologies used for hydrogen production from biomass and biowaste are not yet fully developed into marketable products and to do so many nontechnical issues should be addressed. More generally, the

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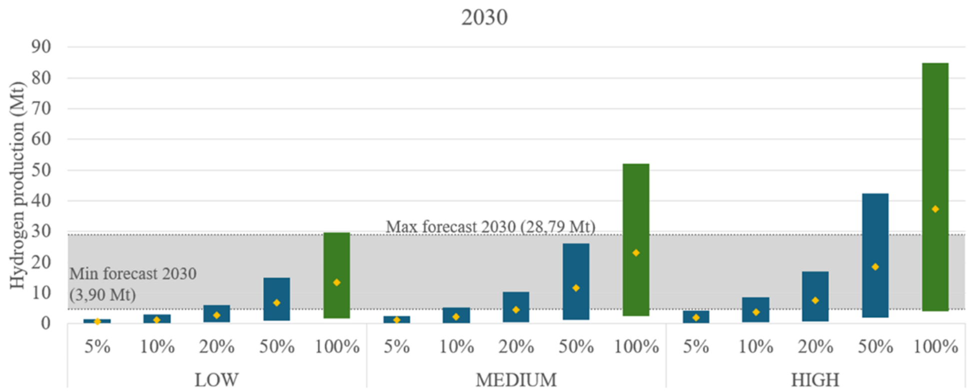

Figure 4. Forecasts of the potential hydrogen production from biomass in EU-27. The bar shows the range between the higher and lower values, considering different technological conversion efficiencies, while the yellow market illustrates the average value. The green bar is distinct from the others because it shows the theoretical production (all of the potential biomass utilized for hydrogen production). The gray area illustrates the range of hydrogen demand in Europe in 2030.

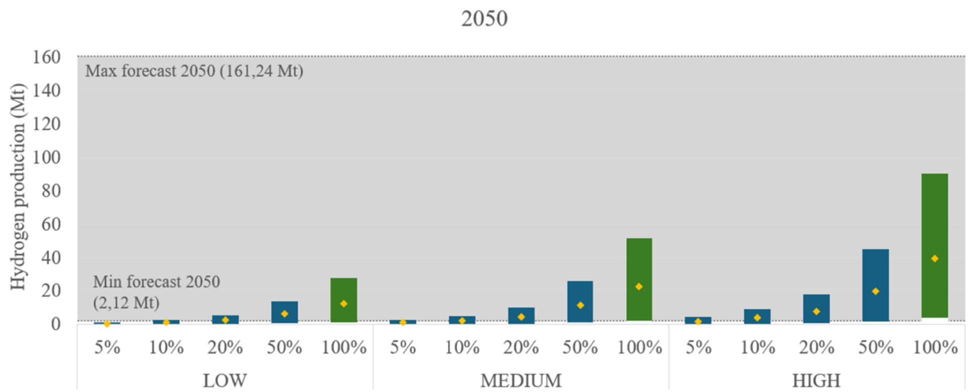

Figure 5. Forecasts of the potential hydrogen production from biomass in EU-27. The bar shows the range between the higher and lower values, considering different technological conversion efficiency, while the yellow market illustrates the average value. The green bar is distinct from the others because it shows the theoretical production (all of the potential biomass utilized for hydrogen production). The gray area illustrates the range of hydrogen demand in Europe in 2050.

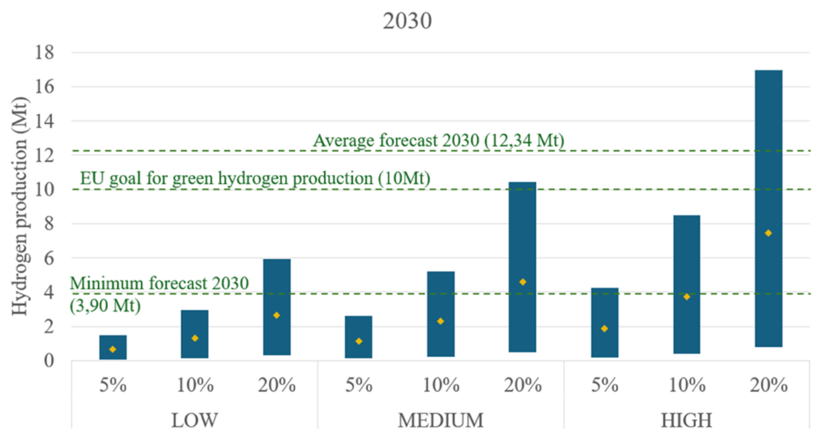

Figure 6. Magnification of the potential hydrogen production in EU-27 by 2030 under three realistic biomass utilization scenarios: 5, 10, and 20%. The green dashed lines indicate the minimum and average hydrogen demand forecasts for 2030, as well as the European goal of achieving 10 Mt of internal green hydrogen production by 2030.

transformation of a scientific (or deep tech) innovation from the lab into marketable products (which represents the whole innovation journey) is a complex process during which many challenges need to be overcome. Such challenges span from technological, policy-regulatory, financial, business development, and operational. Technological challenges concern both increasing the efficiency and scalability of the different processes as well as their system integration with the existing infrastructure/energy system. As regards policy implications, the possibility of producing renewable hydrogen from biomass value chains probably did not receive sufficient attention while focusing on the solar or wind/electrolysis option. First, the sustainability of bioenergy production is already well covered with strict regulation derived from the prescriptions given in

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the Renewable Energy Directive[138] (REDII, with REDIII entering into force in 2026), and large amounts of biomass exist (as estimated in the DG RTD study "Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels"[28]). The production of hydrogen via the biomass route offers a significant advantage, which is the possibility to valorize renewable carbon. This connects hydrogen production to other policies, such as the EU Emission Trading Scheme,[139] which revision will start in 2026. In addition, the Carbon Removal and Carbon Farming initiative by DG Clima[140] will likely pave the way to the inclusion of Carbon Dioxide Removals (CDR) in the EU ETS, adding value to the carbon that through many biomass pathways comes together with the green hydrogen. Given this policy framework, several programs to finance the large investments needed to produce hydrogen from biomass have been carried out by the European Commission, such as the Innovation Fund,[141] the IPCEI[142] program, beyond the smaller-scale actions funded by the Horizon Programme (including the European Innovation Council program) and the Hydrogen Valleys at Member State level.

The main regulatory challenge is the lack of standardized regulations in many areas, such as biomass sourcing and subsidies, such as carbon accounting and credits. Addressing these regulatory challenges to ensure an accelerated transfer to innovation requires coordinated efforts among different stakeholders, such as governments, industry players, and technological organizations to create consistent frameworks. Developing biomass-to-hydrogen projects has high upfront costs and requires substantial investment in facilities and infrastructure. Securing the necessary funding without a certain return on investment can be difficult, especially since many technologies are still in their early stages. Besides, as the blend of different private and public capital changes over time, the right balance of financing options at the right time is crucial to quickly scale the venture and to speed up innovation.[143]

The main private options range from business angels to venture studios and venture capitalists and once the technology is at the FOAK (first of a kind) or NOAK phase (literally meaning that some demo plants have been fully tested) then options such a project finance and private equity are available.[144] Public funding is mainly available as grants or in some cases as governmental equity (venture capital, as done by the European Innovation Council Fund). Successful business development requires strong partnerships with all of the ecosystem players including biomass suppliers, technology providers, policymakers, investors, hydrogen off-takers, and final users. Building a reliable ecosystem, with converging interests of various stakeholders, is particularly challenging, especially in regions where the hydrogen economy is still under development. The public concerns about the sustainability of biomass (e.g., deforestation, food security, and land-use change) represent further major bottlenecks, and there is a need to communicate and inform public opinion on the benefits of such pathways. This will require significant outreach and marketing efforts to ensure a stable and profitable business model. Properly managing the complex biomass supply chain and its successful integration into hydrogen markets require a high degree of operational expertise. Securing smooth operations across these complex networks can be a major challenge for business developers. Addressing these challenges to guarantee the success of biomass-to-hydrogen technologies requires overcoming both technical and market-driven barriers. Technological innovation is not sufficient alone, while sound business strategies, risk-tolerant funding opportunities, collaboration across sectors, and proper regulatory frameworks are also crucial to bring biomass-to-hydrogen technologies to the market.

4. CONCLUSIONS

The study explored the potential production of low-carbon hydrogen from biobased processes in Europe, and their contribution to achieve the EU hydrogen goals for 2030 and 2050. Pyrolysis technologies showed encouraging results, achieving the highest average conversion rate of 65.44 $g_{H2}/kg_{biomass}$. Biological processes presented a lower conversion rate, ranging between 1 and 60 $g_{H2}/kg_{biomass}$, with average values in the order of 20.36 $g_{H2}/kg_{biomass}$.

The analysis also included increasing shares of available biomass for energy purposes, ranging between 310.6 and 836.6 Mt of dry matter by 2030, and reaching a hydrogen yield of over 16 Mt in the best-case scenario. Considering the European goal on hydrogen production for the same year, this is a promising result that suggests the significant contribution that these processes could have on the defossilization of hydrogen production in the medium term.

The study also identified several challenges and areas that require further investigation. Biomass availability, while promising, varies significantly by region and depends on factors such as land use, agricultural practices, supply chain costs, and competing demand for other applications. Although some processes of many biobased hydrogen conversion processes are close to commercialization, others are still in earlier stages and this requires significant investment and development to reach the technological maturity.

Looking to the future, a clear strategic vision for cross-sectoral and systems-integrated hydrogen utilization is needed. It is worth mentioning that the production of hydrogen from biomass is not in competition with other green hydrogen processes, which are mainly based on the electrolytic route, but it is complementary to them and, together with them, can support the achievement of the EU hydrogen targets. With the right support and investment, biobased hydrogen can contribute to the EU's 2030 and 2050 decarbonization goals and support a sustainable energy transition.

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Notes

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