TECHNICAL NOTE

HYDROGEN AND BIOMASS
Opportunities for Hydrogen Production and Hydrogen Use within Bioenergy Systems

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Director of Division of Oil, Gas and Biofuels Studies
Heloisa Borges Bastos Esteves

Executive Coordination
Angela Oliveira da Costa

Technical Coordination
Angela Oliveira da Costa
Rachel Martins Henriques
Rafael Barros Araujo

Technical Team
Angela Oliveira da Costa
Danielle Borher de Andrade
Danilo Perecin
Rachel Martins Henriques
Rafael Barros Araujo
Rafael Belém Lavrador
Vitor Manuel do Espírito S. Silva

Interns
Giovana Carpenter Casini
Miguel Angelo Alvarenga de Carvalho
Pedro Henrique Menegotto Weingartner
João Pedro Rachid Braga

Administrative Support
Raquel Lopes Couto

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Public Value

EPE conducts studies and research to support the formulation, implementation, and evaluation of Brazilian energy policy and planning.

This Technical Note contributes by analyzing the opportunities and synergies between **hydrogen and bioenergy**, two complementary pillars for the Brazilian energy transition. The study reveals a mutually beneficial relationship: while **biomass, an abundant national resource, offers unique attributes for hydrogen production, hydrogen**, in turn, **offers new possibilities for adding value to biomass**, expanding its potential applications and economic impacts.

By publicizing arrangements and possibilities to boost both sectors, EPE aims to clarify the debate and strengthen the national energy planning capacity, promoting **energy transition strategies aligned with Brazil's potential, challenges, and competitive advantages**. This approach seeks to ensure energy security, competitiveness, and sustainability, consolidating the country as a leading player in both national and international energy landscape.

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1. Introduction

Low-carbon hydrogen[1] stands out as a prominent energy alternative in the current context of accelerated energy transition primarily driven by efforts to mitigate climate change and strengthen energy supply security. Hydrogen has become a central element of national plans for reducing greenhouse gas (GHG) emissions across the globe, which aligns with several renewed industrial policies that incentivize less carbon-intensive pathways and foster innovative technologies and the development of new hydrogen-related markets (IEA, 2024a).

One of hydrogen's main assets is its versatility as an energy carrier, a feature deriving from the diversity of production pathways and the range of sectors in which it can be used. Particularly, hydrogen is seen as a potential solution for hard-to-abate sectors[2], either through the direct use of pure hydrogen or indirectly using hydrogen-derived products.

Hydrogen production from water electrolysis using renewable energy sources, such as wind and solar, has become increasingly promising worldwide, driven by learning curves and economies of scale that increased competitiveness. In this regard, Brazil stands out as a particular interesting case, as the country presents favorable natural resources for renewable electricity generation and a well-established low-emission power generation system, based on hydropower and an interconnected grid supported by thermal power plants. These attributes can lead to a safe expansion of non-controllable electricity sources and the production of clean hydrogen when connected to the grid. In 2023, the share of renewables in Brazilian electricity supply was at 89% when considering the whole power mix, and at 93%, when considering only the National Interconnected System[3] (EPE, 2024a).

Another established condition in Brazil that can leverage national opportunities for low-carbon hydrogen production is the contribution of biomass to the country's energy mix. In 2023, biomass accounted for nearly one-third of the country's domestic energy supply, ranking second in market share behind oil and oil derivatives. Biomass contributions are distributed as follows, relative to the entire energy supply: 16.9% from sugarcane, 8.6% from firewood and charcoal, and 5% from black liquor and other biomass sources. Such a significant bioenergy share significantly contributes to the achievement of the cleanest energy matrix among G20 countries (IEA, 2024b). Ethanol and biodiesel production are particularly noteworthy, leading to a transport energy consumption in Brazil with 22.5% share of renewability in 2023 (EPE, 2024a). The country is the second-largest global producer of biofuels, behind the United States (EI, 2024).

Agricultural activity forms the basis of bioenergy production. Brazil's rise as an agricultural powerhouse can be illustrated using data for some of the main global crops and foods, as shown in

[1] Throughout this document, the terms "low-carbon hydrogen," "low-emission hydrogen," and "low-carbon-emission hydrogen" are considered synonymous, all referring to hydrogen produced in a manner that significantly reduce life cycle GHG emissions compared to conventional fossil-fuel-based pathways.

[2] Hard-to-abate sectors are understood as those where emission reduction alternatives are technically complex and/or economically non-competitive with current technology. Regarding energy use, these are applications that usually rely on fossil fuels and are difficult to directly electrify.

[3] Excludes Isolated Systems, Imports, Self-Generation Not Injected into the Grid, and Micro- and Mini-Distributed Generation (MMGD).

Table 1. There remains further potential to increase this production through a range of measures[4], including improvements in productivity and the expansion of agriculture into degraded areas. Furthermore, the introduction of new crops aligned with current and future energy transition can be envisaged, which may further increase bioenergy development.

Table 1*. Main agricultural products production and exportation – Brazil.*

Product	Production				Exportation		
	Million tons [Mt]	World ranking	Global market share [%]	10-Year projection [Mt]	Million tons [Mt]	Global trade ranking	Share of global exports [%]
Sugar	45	1st	25%	55	36	1º	57%
Soybean	153	1st	39%	199	104	1º	59%
Corn	122	3rd	10%	153	46	2º	23%
Orange	15	1st	22%	16	10	1º	30%
Coffee	3,7	1st	29%	4,3	2,1	1º	27%
Cotton	3,2	3rd	13%	4,6	2,7	1º	28%
Beef	10	2nd	19%	11	3,6	1º	28%
Chicken meat	15	3rd	11%	19	5	1º	36%
Pork meat	5,3	4th	4%	6,8	1,5	3º	14%

Source: EPE based on (USDA, 2024); (MAPA, 2024); (OUR WORLD IN DATA, 2023).

Considering Brazilian prominent agricultural production, the country's former experience, the positive outlook for national bioenergy, and the emergence of hydrogen as a prominent solution for decarbonization, the Technical Note "Hydrogen and Biomass" aims to explore the opportunities and synergies between hydrogen and bioenergy.

This study addresses different dimensions of the relationship between these two sectors. On one hand, biomass is highlighted as an abundant source with unique attributes for hydrogen production. On the other hand, it is shown that hydrogen is already essential for bioenergy systems and can potentially be a key input to unlock new pathways that add value to these systems, particularly for fuel production.

Thus, bioenergy is identified as a key partner in building the low-carbon hydrogen value chain in Brazil, potentially serving as a strategic distinctive factor that can lead the country to achieve global leadership and a cutting-edge position in this industry, promoting the realization of its potential. Simultaneously, a widespread, diverse, and competitive low-carbon hydrogen chain can allow Brazil's bioenergy sector to access new markets and expand its economic impacts, ensuring the alignment between increasing energy demands with decarbonization goals and increasingly restrict emission criteria.

This document is structured in seven chapters. *Chapter 2*, following this Introduction, is dedicated to detailing the potential pathways for hydrogen production from biomass. Descriptions of the main processes are presented, with emphasis on thermochemical pathways, which can convert feedstocks such as biogas/biomethane, ethanol, glycerin, and lignocellulosic biomass into hydrogen.

Contributing to supply is not the only way bioenergy can participate in the promising hydrogen market. *Chapter 3* presents a mapping of hydrogen demand within bioenergy production chains, both directly and indirectly, in the form of hydrogen derivatives.

[4] The fact sheet "Potential of Land-Sparing Techniques in Biofuel Production in Brazil," published by EPE in 2024, illustrates techniques that could make land use more efficient, without competing with food production or requiring agricultural land expansion, while maximizing biofuel production (EPE, 2024b).

Chapter 4 addresses the production of synthetic fuels, a particularly interesting case of hydrogen use. Synthetic fuels consist of hydrocarbons that are analogous to petroleum derivatives, enabling the utilization of existing distribution infrastructure and end-use equipment. Biomass-derived hydrogen presents a strategic advantage to produce these fuels, as the feedstock provides not only hydrogen but also the carbon required for hydrocarbon synthesis.

Chapter 5 discusses an essential attribute of hydrogen supply for decarbonization: carbon intensity. Since the underlying goal of hydrogen development is to mitigate climate change, its production must ensure low GHG emissions. The chapter emphasizes the specificities of emission quantification for biomass-based pathways.

Chapter 6 presents an integrated assessment of the relationships between bioenergy and hydrogen, including promising business models and examples of projects at the interface of these sectors, with a focus on Brazil.

Finally, this report concludes with the Final Considerations in *Chapter 7*, which revisit the main conclusions regarding the synergies and mutual benefits between bioenergy and hydrogen, highlighting that this combination can catalyze an energy transition aligned with national interests.

This Technical Note continues a series of publications by the Energy Research Office (EPE) aiming the providing of information on hydrogen, with particular focus on its production pathways. EPE has published a study on hydrogen produced in oil refineries; specific reports on pathways derived from natural gas, including the currently dominant route of the so-called gray hydrogen and the emerging blue hydrogen, which includes carbon capture, utilization, and storage (CCUS[5]); and further reports on the gas pyrolysis route, classified as turquoise hydrogen (EPE, 2022a; EPE, 2022b; EPE, 2022c; EPE, 2022d).

The color-based classification, although useful for identifying groups of production pathways, has been increasingly abandoned globally due to its limitations in capturing the truly essential attributes of hydrogen, such as carbon intensity. The approach of not discriminating hydrogen by its production route aligns with the principle of resource and technology diversity advocated by EPE (EPE, 2021) and adopted by the National Policy for Low-Carbon Hydrogen (BRASIL, 2024a), which aims to "promote various production pathways for low-carbon hydrogen and its derivatives, in order to enhance the country's multiple economic strengths."

In this study, EPE avoids color-based references and does not assign a specific color to biomass-based technologies, referring to the product of these pathways as "biomass-derived hydrogen", "hydrogen from biomass" or "biohydrogen."

[5] Acronym for *carbon capture, utilization and storage* – CCUS.

2. Technological pathways and feedstock for H_2 production from biomass

Global hydrogen production reached 97 million tons (Mt) in 2023, dominated by fossil feedstock, particularly natural gas. Low-carbon hydrogen accounted for less than 1% of total global production, mostly from projects with CCUS (IEA, 2024a).

As a result, CO_2 emissions associated with hydrogen production and use reached 920 Mt in the same year (IEA, 2024a), representing approximately 2.5% of total energy-related global GHG emissions[6]. Therefore, the establishment of a large-scale low-carbon hydrogen supply is required to transform the existing systems even if hydrogen demand remains unaltered.

Additionally, as pressure and incentives for decarbonization expand across all areas, hydrogen emerges as a promising solution for sectors with higher technical complexities or costs to reduce emissions. Numerous studies indicate that hydrogen adoption would be prioritized in these sectors; in this context, it could be used in new applications including hard-to-abate activities in industry, long-distance transport, and long-duration energy storage, among others (AGORA & GUIDEHOUSE, 2021; IRENA, 2022a; WAKIN & TOVAR, 2023; LIEBREICH M. , 2023). Processes associated with bioenergy stand out within both traditional and emerging hydrogen demand, as many production steps use the molecule as input or intermediate, which will be addressed in Chapter 3.

Therefore, supplying low-carbon hydrogen stands out as an important task for energy transition. Hydrogen production from biomass represents a feasible low-carbon alternative (IEA, 2024a). The following sections aim to clarify the main technological routes and potential feedstocks that can be used for hydrogen production from biomass.

2.1. Biobased feedstock

In the context of bioenergy and bioeconomy, biomass can be defined as any renewable resource derived from organic matter, whether of animal or plant origin, that can be used to generate energy and chemical products. The global domestic supply of bioenergy in 2021 was 54 EJ[7], with 85% coming from solid biomass sources such as wood chips, wood pellets, and traditional biomass sources. Liquid biofuels accounted for 7%, the municipal and industrial waste sectors accounted for nearly 3%, and biogas accounted for 2% (WBA, 2024).

According to IRENA, biomass has significant potential to increase energy supply in populous countries such as Brazil, India, and China (IRENA, 2023). The NPP (*Net Primary Production*) is an indicator that can be used to assess a country's biomass availability. This indicator measures the amount of carbon fixed by plants and accumulated as biomass per year; in other words, it reflects the productivity of planted biomass. The average NPP in Brazil is 8.5 tons of carbon per hectare per year (tC/ha/year), as shown in *Figure 1*. This corresponds to a very high level of biomass productivity, as the global average NPP is approximately 3–4 tC/ha/year (IRENA, 2024).

[6] This includes direct emissions from hydrogen production and approximately 300 Mt of CO_2 used in the synthesis of urea and methanol, which are mostly released into the atmosphere. Emissions from hydrogen coproduced in naphtha cracking and steam cracking processes are not accounted for, nor are emissions from the fossil fuel supply chain (upstream and midstream) (IEA, 2024a). The global total energy-related emissions reached 37.4 Gt CO_2 in 2023 (IEA, 2024c).

[7] EJ refers to exajoules, with the prefix "exa" corresponding to 10^{18} in the International System of Units. For comparison, the global primary energy supply is on the order of 620–630 EJ (EI, 2024; IEA, 2024d).

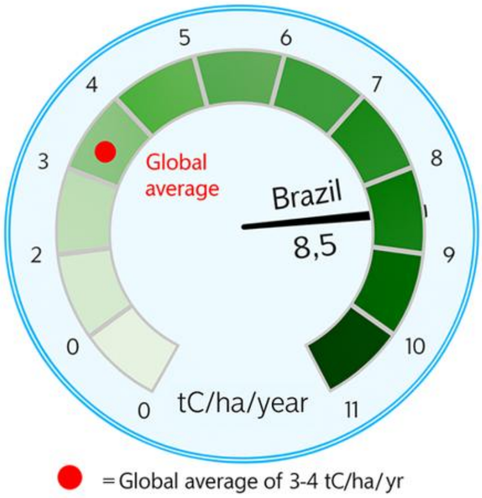

Figure 1. Biomass Potential: Net Primary Production (NPP) – Brazil
Source: Adapted from (IRENA, 2024)

As a biological resource, biomass is primarily composed of compounds that are rich in carbon, hydrogen, and oxygen. Therefore, it stands out as a potential feedstock for the development of alternative production routes for fossil-derived products, including hydrogen. Biomass consumes atmospheric carbon during agricultural production. Thus, CO_2 emissions during the use of biomass-derived products do not represent a net addition to the atmosphere as they are part of a cyclical process of regeneration and consumption, which stands out as a strategic advantage of biomass. However, the chemical attributes of biomass pose processing challenges, either due to the presence of undesired chemical elements (e.g., oxygen, nitrogen, sulfur, etc.) or due to the greater structural complexity of molecules derived from plants and animals. Consequently, industry has traditionally relied on biomasses of low complexity for biofuel production, including feedstocks that are rich in lipids, sucrose, and starch. These feedstocks are known as non-lignocellulosic biomass, or first-generation biomass, and are illustrated in *Figure 2*. Biomasses that are rich in sucrose or starch are traditionally used for bioethanol production; vegetable and animal oils and fats are used for biodiesel production; and food residues are used for biogas production. The use of these traditional biomass sources deriving from sugarcane, corn, soy, cotton, among others, is established in Brazil.

Beyond traditional biomass sources, there is significant potential for energy recovery and advanced solutions from alternative biomass, such as sugarcane residues (bagasse and tops, vinasse, and filter cake), residues from the wood industry (chips), straw from soybean and corn crops, rice and coffee husks, coconut, bean, peanut, cassava, and cocoa residues, agro-industrial and confined livestock waste, sewage sludge, and municipal solid waste (MSW) (EPE, 2024). These feedstocks are mostly known as lignocellulosic or second-generation biomass and are primarily composed of three components: cellulose, hemicellulose, and lignin, as illustrated in *Figure 2.*

Cellulose and hemicellulose are polysaccharides and, therefore, potential sources of sugars for chemical and biochemical processes. However, processing lignocellulosic biomass to make carbohydrates accessible is more complex and costly than processing non-lignocellulosic biomass. This occurs due to several natural barriers such as the high crystallinity of cellulose and its elevated degree of polymerization, which directly impact the conversion of these sugars. In addition, lignin acts as a natural barrier to polysaccharide conversion due to its structural role within plant cell walls and its hydrophobicity (RABELO, SCOPEL, ARAUJO, BRETAS, & COSTA, 2023). Thus, lignocellulosic biomass is usually used for thermal energy generation, which dismisses prior biomass processing.

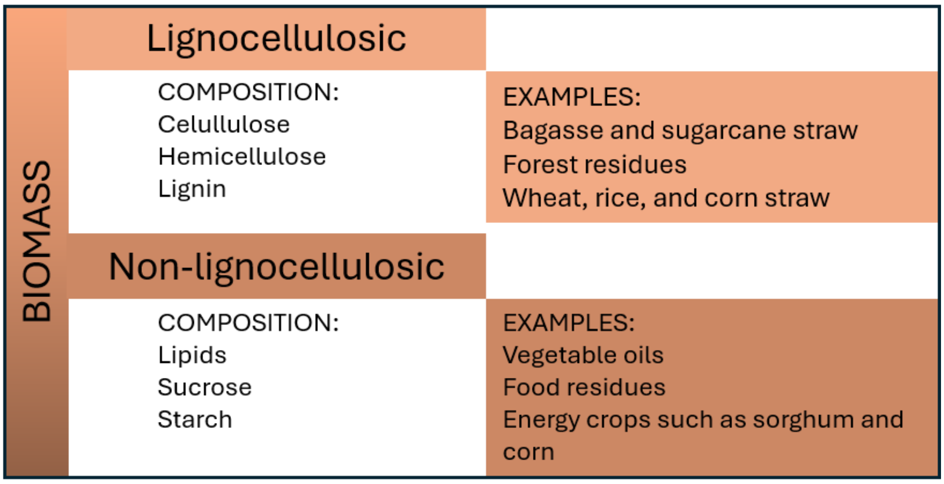

Figure 2. Biomass classification, composition and examples.
Source: EPE from (RABELO, SCOPEL, ARAUJO, BRETAS, & COSTA, 2023)

Both first-generation and second-generation biomass constitute possible feedstocks for low-carbon hydrogen production. Second-generation biomasses constitute potentially more favorable alternatives for this purpose, as they do not compete in higher-value markets.

In simplified terms, hydrogen generation processes from biomass rely on the decomposition of complex biological products into more elementary molecules. They can be carried out through thermochemical, biological, or electrochemical pathways, as described in the following section. Cellulose and hemicellulose are susceptible to biological degradation and H_2 production, whereas lignin is not biodegradable. Therefore, pretreatment, hydrolysis, and lignin removal are necessary in biological routes to obtain high-purity H_2 (ELHAMBAKHSH et al., 2023). Thermochemical pathways, on the other hand, do not require such pre-processing. For this reason, they constitute simpler methods for decomposing lignocellulosic materials for hydrogen production and are currently the most widely used technologies. Electrochemical processes for biomass-to-hydrogen conversion, in turn, are still at an early stage of development.

2.2. Hydrogen Production Pathways

The main routes for producing hydrogen from biomass are classified into three technological platforms: Thermochemical Pathways, Biological Pathways, and Electrochemical Pathways *(Figure 3*), detailed below.

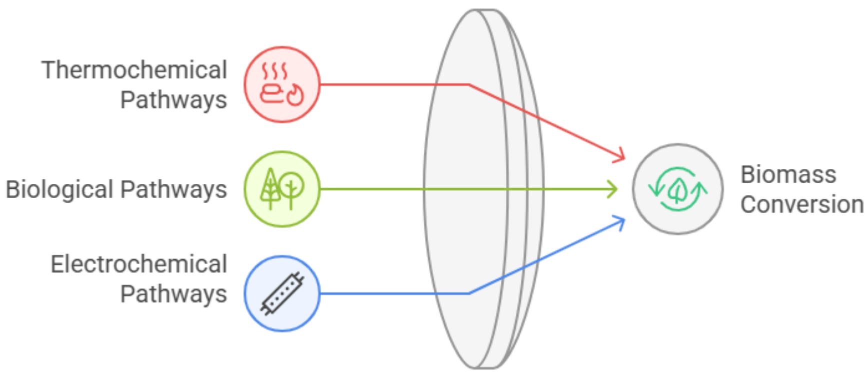

Figure 3. Main H_2 production pathways from biomass.
Source: EPE, supported by Napkin

2.2.1. Thermochemical Pathways

Thermochemical conversion is the most mature technology for hydrogen production from biomass (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021). It consists of using heat, pressure, and catalysts to break biomass chemical bonds and generate gaseous products. The three main thermochemical conversion routes are gasification, reforming, and pyrolysis.

Synthesis gas

"Synthesis gas" obtained from thermochemical processes is essentially a mixture of hydrogen (H_2) and carbon monoxide (CO) and may also contain carbon dioxide (CO_2) and water vapor (H_2O).

In addition, minor compounds can also be present, such as light hydrocarbons, tar, hydrogen sulfide (H_2S), hydrogen chloride (HCl), ammonia (NH_3), and alkali metals (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021).

High-purity hydrogen production through thermochemical biomass conversion routes depends on the purification of the gases produced in the processes, which consist of mixtures rich in H_2 and low-molecular-weight carbon compounds such as CO, CO_2, and CH_4. Specifically, synthesis gas stands out as the main product of gasification and reforming routes. Biomass pyrolysis, in turn, generally produces gases containing higher methane content, especially at lower temperatures, which requires additional steps to obtain conventional synthesis gas (WARDACH-SWIECICKA & KARDAS, 2023).

Synthesis gas purification is a complex process that occurs into additional costs, which increases with the required hydrogen purity. At the same time, synthesis gas can be directly converted into synthetic fuels, as described in Chapter 4, avoiding the need for purification. Thus, biomass-derived hydrogen from thermal routes is particularly suitable for downstream chemical-conversion pathways, which justifies the emphasis given to these applications in this document.

Gasification

Gasification is suitable for producing hydrogen from lignocellulosic biomasses, which offer additional potential for the generation of biofuels and value-added products. Other feedstock that can be used in gasification include food waste, wood residues, and municipal solid waste (MSW)[8].

Biomass gasification is a highly endothermic process carried out in an oxygen-deficient environment in the presence of a gasifying agent, which can be air, oxygen, or steam. The process takes place at temperatures ranging from 800 to 1000 °C. The resulting gas mixture is the synthesis gas, previously defined.

The Lower Heating Value (LHV) of synthesis gas ranges from 4 to 13 MJ/Nm^3, depending on its composition, which, in turn, is influenced by the feedstock, the employed technology, and the operating conditions. Char, a by-product of the process, consists of unconverted organic fractions that become carbon and ash. The amount of unconverted organic matter depends primarily on the gasification technology and operating parameters, while the ash content depends mainly on the type of biomass used. The LHV of char typically ranges from 25 to 30 MJ/kg, depending on the amount of unconverted organic fraction (MOLINO, CHIANESE, & MUSMARRA, 2016).

[8] Additionally, gasification using mixtures of plastic waste and biomass have been the subject of research and development efforts (RUBINSIN, et al., 2023).

In simple terms, biomass gasification involves the following reactional zones: drying; pyrolysis; oxidation (combustion); and reduction, in which the main chemical reactions occur. The energy required for these reactions is generally supplied by the oxidation of biomass fractions.

The gasifier is the equipment (reactor) in which gasification reactions take place. Within it, biomass, in contact with the gasifying agent, has its chemical bonds broken, producing synthesis gas and char. The gasifier choice must primarily consider the type of biomass and its attributes, the gasifying agent, and upstream operations. Among the available gasification technologies, fixed-bed gasifiers, fluidized-bed gasifiers, supercritical water gasifiers, and plasma gasifiers stand out (*Figure 4*).

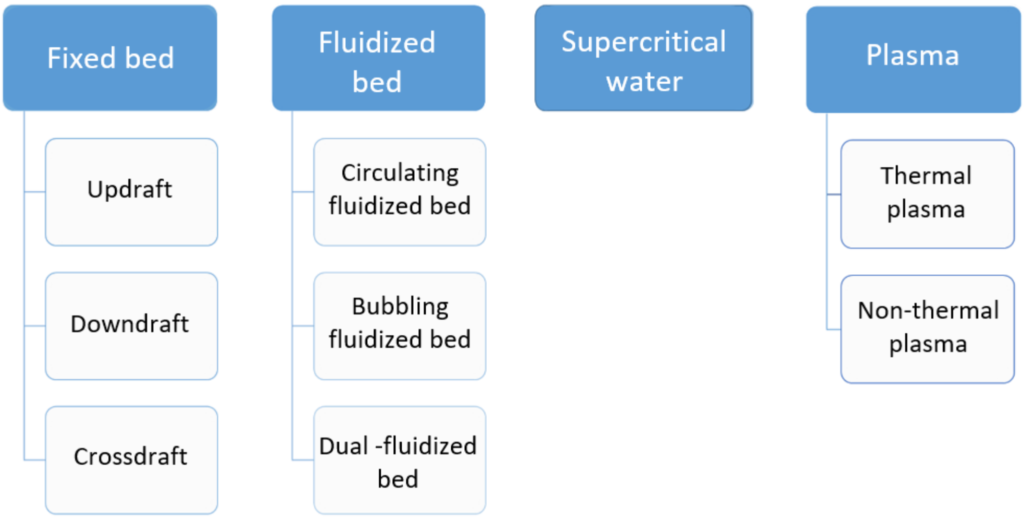

Figure 4. Types of gasifiers
Source: EPE

Fixed-bed gasifiers are easy to construct, more economical, and simple to operate, being suitable for small-scale applications. They produce cleaner synthesis gas with low tar content; however, the biomass/gasifying agent mixture has low homogeneity and a long residence time, which results in a lower heat transfer and a product with lower calorific value. Depending on the entry point of the gasifying agent into the reactor, fixed-bed gasifiers are classified into three types: (i) updraft; (ii) downdraft; (iii) crossflow (MAHINPEY et al., 2023; RUBINSIN, et al., 2023).

Fluidized-bed gasifiers have gained prominence due to their flexibility regarding biomass feedstock and high efficiency, enabling both small- and large-scale operations and providing cost advantages in terms of operational expenses (OPEX) and capital expenditure (CAPEX). They are classified into three types: circulating fluidized bed, bubbling fluidized bed, and dual fluidized bed. Due to its ability to produce synthesis gas with a high hydrogen concentration and lower tar levels, the dual fluidized-bed gasifier has recently attracted industrial attention (RUBINSIN, et al., 2023).

Supercritical water gasification (SCWG)[9] stand out as an alternative for H_2 production, as it consists of a more resilient process to different types of biomasses, such as carbohydrates, wood, and wet biomass, and produces low pollutant emissions. The entire process is endothermic and can be carried out with lower residence times (2–6 s) and lower temperatures (600–650°C) than conventional gasification. However, sustaining these conditions requires considerable energy input, which increases costs and limits the scalability of the process (ELOFFY et al., 2022).

Plasma gasifiers operate at high temperatures (up to 10,000 °C), which benefits tar decomposition. Tar presence is one of the main challenges in conventional gasification, as it causes equipment clogging and deposition on catalysts, restricting the use of the resultant synthesis gas to combustion rather than more advanced production of fuels and chemicals (SANJAYA & ABBAS, 2022).

At industrial scale, gasifiers differ essentially in: (i) the way the feedstock (biomass) and the gasifying agent contact; (ii) the rate and conditions of heat transfer; and (iii) the residence time of the feedstock in the reaction zone (MOLINO, CHIANESE, & MUSMARRA, 2016).

Gasification using steam as gasifying agent presents higher H_2 yield (40%) and higher H_2/CO ratio (1.6). Furthermore, regarding biomass feedstock, steam gasifiers accept a moisture content of around 5–35% by mass, whereas air gasifiers require dry biomass (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021). In addition to the gasifying agent, other operational parameters must be monitored due to their impact on the gasification process, namely: biomass type and particle size, temperature, steam/biomass ratio, catalyst, and residence time.

To enhance hydrogen production, a water-gas shift (WGS) reactor can be integrated downstream of the gasification process. The WGS reaction involves transforming carbon monoxide (CO) and water into hydrogen (H_2) and carbon dioxide (CO_2), as shown in Equation 1:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad \text{Equation 1}$$

Additionally, a hydrogen purification system must also be included downstream to separate H_2 from other synthesis gas components. Among the available technologies, the use of molecular sieves is particularly relevant, resulting in operations known as PSA (*Pressure Swing Adsorption*)[10]. Such processes can yield H_2 streams with very high purity (up to 99.9%).

Furthermore, a CO_2 capture unit could be added to recover the gas from tail gas (PSA residual outlet). One technological solution for this is chemical absorption using amines, such as monoethanolamine (MEA), in a cyclic process with solution regeneration and high-temperature CO_2 release. Obtaining high-purity CO_2 permits its use and/or permanent storage, potentially generating new revenue and/or reducing the carbon intensity of hydrogen, even potentially to negative values (PANG, 2023).

Figure 5 shows the basic configuration of an integrated H_2 production system from biomass, using gasification, a WGS reactor, H_2 purification via PSA, and CO_2 purification via MEA.

[9] To create a supercritical fluid, water must be heated to a temperature above 374°C and pressurized above 221.2 bar. Under these conditions, organic molecules and gases exhibit excellent miscibility with supercritical water, accelerating the conversion process.

[10] Adsorption enables the separation of a gas mixture based on the different affinities of each gas species with an adsorbent, such as molecular sieves. The PSA method works in adsorption and regeneration cycles, in which the adsorbent regenerates due to pressure variation (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021).

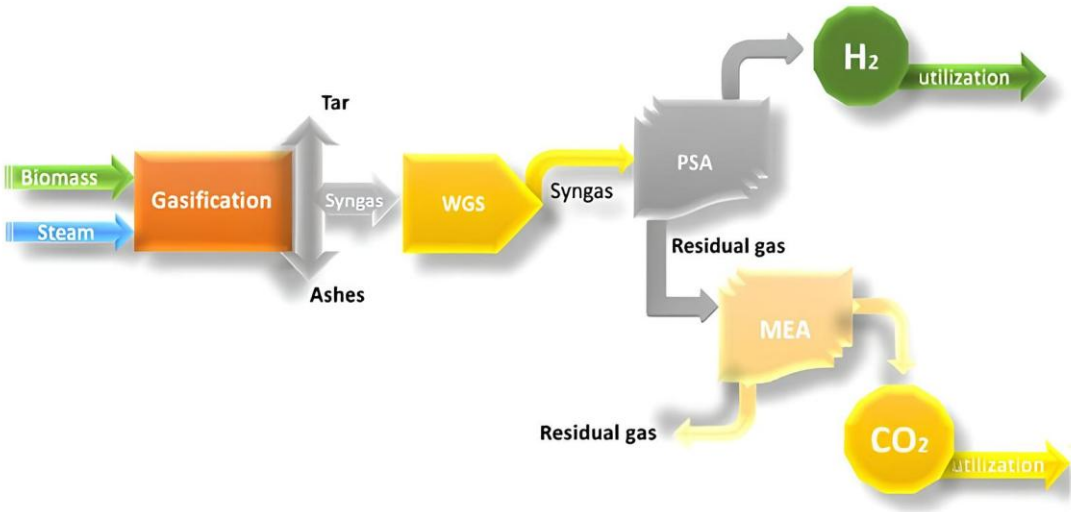

Figure 5. Basic H_2 production configuration from biomass via gasification with integrated technologies (WGS, PSA, and MEA).

Each of these technologies presents very high development potential. Innovation, research, and development activities have recently intensified to increase hydrogen yield with efficiency, lower cost, and sustainability. Currently, the technological readiness level (TRL) of each individual step of hydrogen production from biomass through gasification is considered high. However, the integration of the processes and resulting streams is still at a lower maturity level, requiring further development to enable industrial-scale operation (IEA BIOENERGY, 2025).

Reforming

Reforming operations consist of a series of catalyzed reactions that convert hydrocarbons, mainly alkanes and alkenes, into other products. Reforming reactions are fundamental processes in the chemical and energy industries. The main goal of these reactions is to produce synthesis gas.

There are different types of reforming. The most relevant ones are listed below and exemplified using the reactions occurring with methane (CH_4):

a) **Steam Reforming**: In this process, methane (from natural gas or biogas) reacts with steam at high temperatures (700–1,000°C), as shown in Equation 2:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad \text{Equation 2}$$

b) **Dry Reforming**: In this method, the reaction occurs without the addition of steam. Methane is converted into hydrogen and carbon monoxide through a reaction with carbon dioxide, as shown in Equation 3:

$$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2 \qquad \text{Equation 3}$$

c) **Oxidative Reforming**: In this case, the hydrocarbon is oxidized in the presence of oxygen, also producing synthesis gas, as shown in Equation 4:

$$2CH_4 + O_2 \rightleftharpoons 2CO + 4H_2 \qquad \text{Equation 4}$$

Steam methane reforming (SMR) is the most used H_2 production technology globally, featuring high efficiency and low production cost. Natural gas is usually employed as feedstock for this route. Therefore, the production and export of the main hydrogen derivatives[11] is concentrated in regions with competitive gas prices and abundant fossil fuel supply[12].

However, natural gas reforming is a highly GHG-emitting production pathway. Therefore, combining technologies such as carbon capture[13] or using biomass and biofuels as feedstocks (particularly biomethane) represents a promising alternative for decarbonizing hydrogen supply and, consequently, the global industrial and refining sectors, enabling the continued operation of existing hydrogen generation units.

The conventional steam reforming process, described in (EPE, 2022b), comprises the following steps: feedstock pretreatment; reforming reaction; shift reaction; and hydrogen purification. Pretreatment involves hydrodesulfurization (HDS) to remove contaminants that negatively affect catalyst efficiency, followed by pre-reforming operation, which converts heavier hydrocarbons into methane, reducing coke formation (QUELHAS, SOUSA, SANTOS, & BRASIL, 2012). HDS operation is dispensable if biomethane and/or natural gas are used under conditions specified by current regulations, while pre-reforming is unnecessary for biomethane since anaerobic digestion does not produce hydrocarbons with chains longer than CH_4.

In the steam reforming process, methane reacts with steam at temperatures between 800 – 1,200°C under pressures of 3 – 25 bar in the presence of a catalyst. This approach produces three moles of H_2 and one mole of CO per mole of converted methane (Equation 2).

Methane reforming reaction is endothermic; therefore, the process requires heat input. High temperatures are also needed because the activation of a highly symmetrical methane molecule with strong C – H bonds requires significant energy. Furthermore, as temperature decreases, carbon deposition on the catalyst intensifies, which reduces its efficiency (STENINA & YAROSLAVTSEV, 2022; QUELHAS, SOUSA, SANTOS, & BRASIL, 2012).

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[11] Hydrogen derivatives are mainly understood as methanol, ammonia, and ammonia-based products, such as nitrogen fertilizers.

[12] This statement can be exemplified by the high hydrogen production observed in regions such as the Middle East and the United States (IEA, 2024a), Russia's and Middle East's position in the export of urea and nitrogen fertilizers (BRASIL, 2023), and the dominance of the Middle East, the United States, and Trinidad and Tobago in the global methanol market (WORLD BANK, 2025). China is an exception, appearing among the largest global producers of H_2, urea and fertilizers and methanol, despite being an importer and facing relatively high natural gas prices. However, more than two-thirds of hydrogen produced in China is based on coal gasification, making it the only country with significant production via this pathway (IEA, 2022).

[13] The example of incorporating carbon capture is detailed in EPE's publication on natural gas hydrogen with CCUS (EPE, 2022c).

From the production of synthesis gas onwards, the steam reforming and gasification processes are analogous[14]. Following reforming, if the main goal is to increase hydrogen production, the conversion of carbon monoxide in the presence of steam is required (Equation 1, WGS). Then, to obtain a pure product, the subsequent step is the separation of H_2, typically based on adsorption.

From waste to hydrogen

The reforming of biogas or biomethane is a renewable alternative for hydrogen production and an opportunity to add value to waste management systems.

Catalytic reforming (SMR) and conversion (WGS) processes can have their reactions "accelerated" using noble and transition metal catalysts, which exhibit high catalytic activity and resistance to coke formation. However, due to their high cost, their use is still limited. Consequently, nickel-based (Ni –) catalysts, whose activity is comparable to that of platinum (Pt) and iridium (Ir), are more widely used industrially (ZHANG, SUN, & HU, 2021). The use of supports, predominantly oxides such as alumina and silica, increases the degree of conversion and reduces poisoning effects (STENINA & YAROSLAVTSEV, 2022).

The following section describes the applications of reforming for selected biomass-based feedstocks, including biogas and biomethane, ethanol, and glycerin.

Biogas and biomethane

Biogas and biomethane reforming consist of an alternative for hydrogen production. Biogas is produced through the decomposition of various organic wastes via anaerobic digestion. Agricultural residues, animal waste, municipal solid waste, and even sewage from treatment plants are rich sources for biogas production. Biogas is primarily composed of CH_4 e CO_2, and may contain H_2, N_2, O_2, H_2S e NH_3, among other impurities, depending on the substrate and the process and gas capture conditions.

Besides steam reforming, dry reforming has also emerged as a technological option for biogas reforming as its two predominant components are the reaction's reactants. Some potential advantages of this pathway include: reduced water consumption compared to steam reforming; eliminating the need for biogas purification to biomethane; consumption of two greenhouse gases concomitantly (CH_4 e CO_2); and the possibility of producing synthesis gas under conditions more favorable for fuel production in terms of the H_2:CO (OLIVEIRA, et al., 2021). A pilot-scale plant based on biogas dry reforming was commissioned in 2024 in Foz do Iguaçu, aiming to generate syncrude for refining and aviation fuel production (ITAIPU PARQUETEC, 2024).

Additionally, Basso et al. (2023) describe the hydrogen production from landfill biogas by integrating steam reforming with low- and high-temperature electrolysis[15] and H_2 purification processes[16]. Such hybrid configurations offer the advantage of heat recovery, with electrical and thermal outputs fully utilized to supply all system components (BASSO et al., 2023).

Ethanol

The use of ethanol (CH_3CH_2OH) as a feedstock for steam reforming constitutes a promising alternative for low-carbon hydrogen production. Bioethanol is produced from sugar and starch

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[14] The processing of synthesis gas resulting from gasification and reforming is similar, provided that the final objectives of the processes are compatible. It should also be noted that synthesis gas has a variable composition. Therefore, the efforts required at each subsequent stage vary according to the technological route and the feedstock used in its generation.

[15] Low-temperature electrolysis refers to Alkaline Electrolysis Cell (AEC) and Proton Exchange Membrane Cell (PEM or PMEC) technologies. High-temperature electrolysis refers to the Solid Oxide Electrolysis Cell (SOEC) (BASSO et al., 2023).

[16] The processes of Pressure Swing Adsorption (PSA) and chemical absorption were considered (BASSO et al., 2023).

fermentation. It is characterized as a clear, volatile, water-soluble, and flammable organic liquid with polar properties due to its hydroxyl (OH) functional group.

The main thermochemical processes for hydrogen production from ethanol reforming are: (i) ethanol steam reforming (Equation 5), (ii) ethanol partial oxidation (Equation 6) e (iii) ethanol autothermal reforming (Equation 7) (CHEN et al., 2023).

$$CH_3CH_2OH + 3H_2O \rightleftharpoons 6H_2 + 2CO_2 \quad \text{Equation 5}$$

$$CH_3CH_2OH + 1.5O_2 \rightleftharpoons 3H_2 + 2CO_2 \quad \text{Equation 6}$$

$$CH_3CH_2OH + 1.8\,H_2O + 0.6O_2 \rightleftharpoons 4.8H_2 + 2CO_2 \quad \text{Equation 7}$$

Despite the difference between the operating temperatures of steam methane reforming and steam ethanol reforming, the same catalysts (noble metals, copper, or nickel) are often used in ethanol reforming processes (STENINA & YAROSLAVTSEV, 2022). The catalytic activity of different catalysts and their physicochemical properties govern the thermochemical conversion of ethanol. Reaction conditions vary among the different ethanol reforming methods. Therefore, optimizing catalyst development and conducting a comprehensive, comparative study of catalysts are essential steps to improve hydrogen production (CHEN et al., 2023).

Steam reforming of ethanol produces a hydrogen-rich stream through a highly endothermic process that requires temperatures around 700°C for complete ethanol conversion. In addition, catalyst deactivation occurs over time due to coke deposition and/or sintering. In partial oxidation of ethanol, the energy demand is lower since oxygen is used instead of steam, which leads to an exothermic reaction in which ethanol is converted at low temperatures (250–350°C). However, under these conditions, hydrogen production is reduced. Rodríguez et al. (2023) highlight the use of oxidative steam reforming of ethanol (OSRE), which combines reforming and oxidation reactions (Equation 8). By adjusting the reactant ratio, it is possible to reduce energy costs, operate at milder temperatures (300–600°C), reduce steam consumption and catalyst deactivation, and maximize hydrogen production (RODRÍGUEZ et al., 2023).

$$CH_3CH_2OH + (3-2x)H_2O + xO_2 \rightarrow (6-2x)H_2 + 2CO_2 \quad \text{Equation 8}$$

The use of ethanol for hydrogen production allows using the alcohol as an H_2 carrier. In other words, it takes advantage of safe and well-established ethanol distribution chains and enables on-site conversion to H_2 near the point of consumption, allowing hydrogen refueling while overcoming its logistical challenges. This concept is described in more detail in Chapter 6.

Glycerin

In Brazil, blending biodiesel to diesel is mandatory, with the biodiesel percentage set by the National Energy Policy Council (CNPE). As of April 2025, the current blend is 14% (B14) (MME, 2023). The Future Fuel Law (Brazilian Law No. 14,993/2024) establishes the mandatory biodiesel content within a range of 13% to 25%, allowing blends above 15% only if technical feasibility is demonstrated (BRASIL, 2024b).

Strengthened pathway

The use of glycerin for hydrogen production can enhance the attractiveness of transesterification for biodiesel production.

With the increasing production of biodiesel, there is also a corresponding rise in the generation of the coproduct from the transesterification reaction, glycerol or glycerin, represented by the formula $C_3H_8O_3$ (*Figure 6*).

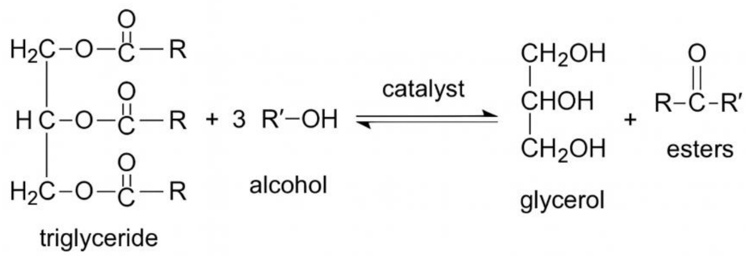


Figure 6. Transesterification reaction for biodiesel (ester mixture) and glycerol (co-product) production.
Source: (NETO et al., 2000)

There are several possibilities for the recovery and economic valorization of glycerin, such as blending it into animal feed, combustion, anaerobic fermentation, and chemical conversion into hydrogen. Utilizing glycerin adds value to a coproduct of the biodiesel industry.

For hydrogen production, the conventional routes are pyrolysis, steam reforming, partial oxidation, and autothermal reforming. All of these involve endothermic reactions, requiring high energy input to convert glycerin into H_2.

Glycerin steam reforming stands out for providing the highest hydrogen yield, the lowest rate of side reactions, and the existence of established industrial equipment for methane steam reforming. Nevertheless, it still faces challenges such as catalyst deactivation due to coke deposition, reduced hydrogen production rate and purity due to side reactions, and high energy demand for glycerin vaporization (MENEZES, 2018).

To overcome these challenges, Chemical Looping Reforming (CLR) has emerged as an alternative for energy generation and synthesis gas production from glycerin. Studied since 2008 by the Gas Processing Laboratory (LPG) of Senai-DR/RN, the main advantages of this route are: zero release of acrolein, a product of glycerin combustion; operation at temperatures above 550°C; not requiring a unit for separating oxygen from atmospheric air; and producing synthesis gas with low CO_2 concentration. Additionally, it can yield synthesis gas at a 2:1 H_2/CO ratio, enabling Fischer-Tropsch synthesis downstream to produce advanced biofuels, such as aviation fuels (OLIVEIRA, et al., 2022).

A pilot plant for fuel production from glycerin from this pathway was inaugurated in the second half of 2023 in Natal-RN, designed to produce 5 L/day of advanced biofuel with the goal of certification and advancement in technical-commercial feasibility assessment (SENAI-RN, 2023; FIERN, 2024). This project is revisited in Chapter 6.

Pyrolysis

Pyrolysis is a thermochemical process that converts biomass into pyrolysis gas, biochar, and bio-oil, typically at temperatures ranging from 400 to 800°C and pressures up to 5 bar, without the presence of oxygen (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021; YOUNAS et al., 2022) The composition of biomass pyrolysis products is often complex due to multiple simultaneous reactions, and the yields can vary depending on the feedstock (biomass), pyrolysis temperatures, heating rates, and catalysts (ZHANG et al., 2023; KAN et al., 2016; SHARMA et al., 2015; COLLARD & BLIN, 2014).

The various types of biomass feedstock are composed mainly of carbon (C), hydrogen (H), and oxygen (O), with considerable variation in other elements. The general pyrolysis reaction converts biomass into high- and medium-molecular-weight organic liquids (tar and aromatic hydrocarbons) and low-molecular-weight organic liquids, which make up the bio-oil. In addition, a gaseous phase is generated, containing typical synthesis gas components, and a solid phase, called biochar.

Based on operating conditions, pyrolysis can be classified as slow, fast, or flash, depending on the heating rate, reaction temperature, and residence time (LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021; YOUNAS et al., 2022).

Pyrolysis gas consists of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2); light hydrocarbons, mainly methane (CH_4); and contaminant gases such as ammonia (NH_3), hydrogen sulfide (H_2S), nitrogen and sulfur oxides, as well as short-chain alcohols. Its typical calorific value ranges from 10 to 20 MJ/Nm³. Pyrolysis gas can be used for heat and electricity generation or even for producing biofuels via the Fischer-Tropsch synthesis process. The final use of the pyrolysis gas requires prior removal of contaminant compounds. Biomass pyrolysis can produce gases with compositions like those of synthesis gas or even gases richer in hydrogen; however, the product typically has a higher methane concentration, requiring additional adjustment steps for H_2 production. In pyrolysis, high moisture content, longer residence time, smaller particle size, and specific catalysts[17] favor hydrogen production (KAN et al., 2016; LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021; YOUNAS et al., 2022).

Research on integrated systems combining fast pyrolysis and steam reforming is underway, aiming to increase H_2 production from bio-oil (SORIA et al., 2019; ARREGI et al., 2023; SINGH et al., 2023).

2.2.2. Biological Pathways

Biological pathways rely on microorganisms, with hydrogen production promoted by the biocatalytic action of their enzymes. In contrast to thermochemical pathways, biological reactions occur at ambient temperature and pressure.

These processes are generally suitable for small-scale production, but face challenges to reach commercial scale. Key difficulties include increasing hydrogen yield and production rates, process duration, high costs, and maintaining system stability at large volumes (SOUZA, 2018; IVANENKO, et al., 2024).

The main biological processes for hydrogen production are dark fermentation of biomass and those that depend on light as an energy source, such as photofermentation and water bio-photolysis.

Dark fermentation is based on the action of fermentative bacteria to produce H_2 under anaerobic conditions, primarily using residual biomass as feedstock. It represents the initial stages of

[17] Noble metal catalysts such as Ruthenium (Ru) and Rhodium (Rh) exhibit good catalytic activity; however, they are extremely expensive, which makes the process economically unfeasible. The use of Nickel (Ni)-based catalysts and Zeolites offers greater feasibility due to lower cost, good selectivity, and catalytic activity (YOUNAS et al., 2022; KAN et al., 2016).

anaerobic digestion, including hydrolysis and acidogenesis, which convert organic matter, especially carbohydrates, into volatile organic acids and hydrogen. Optimizing hydrogen production requires careful control of medium acidity (pH) and hydrogen partial pressure, which must be removed to prevent system displacement away from hydrogen synthesis and toward other byproducts' generation (SOUZA, 2018; IVANENKO, et al., 2024). Brazilian researchers have studied dark fermentation of vinasse from sugarcane ethanol plants, evaluating different configurations and operational conditions, including integrating hydrogen production with biogas generation (FERRAZ JUNIOR et al., 2014; FUESS, et al., 2017).

Water bio-photolysis is carried out by green microalgae and cyanobacteria and involves photosynthesis, either directly or indirectly. In the direct mechanism, the enzyme hydrogenase promotes H_2 generation. In the indirect mechanism, bio-photolysis involves the enzyme nitrogenase and proceeds through the formation of carbohydrates and organic acids (SOUZA, 2018; IVANENKO, et al., 2024).

Photo-fermentation is based on the conversion of organic acids and solar energy through the action of nitrogenase enzymes in photosynthetic or phototrophic bacteria. The process can be conducted in two stages, combined with dark fermentation. It is considered the most recent and least competitive among biological hydrogen production methods (SOUZA, 2018; LEPAGE, KAMMOUN, SCHMETZ, & RICHEL, 2021).

2.2.3. Electrochemical Pathway

Hydrogen production via water electrolysis is a well-known industrial method. Its advantage resides in the possibility to produce high-purity hydrogen without contamination by carbon monoxide (CO) or carbon dioxide (CO_2). However, in most cases, water electrolysis requires significant electricity consumption (4.5–5 kWh/m³ H_2), which results in high costs and limits the competitiveness of the process. In this context, biomass can be considered a potential alternative feedstock for more cost-effective electrolytic hydrogen production. In such cases, low-molecular-weight products like ethanol or glycerol are typically used, either in pure streams or mixed with water. The main advantage of this approach is to utilize organic material both as a hydrogen source and as an electron donor to reduce electricity consumption for electrolysis (LIU et al., 2020).

Microbial electrolysis cells (MECs) and proton exchange membrane electrolysis cells (PEMECs) are the two technologies with the greatest potential for biomass electrolysis. These systems require one or two chambers with an anode/cathode coupling. The anode reaction is what differentiates water electrolysis from biomass electrolysis. Instead of generating gaseous O_2 from water, biomass is electrochemically oxidized, producing H^+ protons and oxidation products such as CO, CO_2, and water. The H^+ protons then migrate through a membrane. Reduction reactions occur at the cathode, resulting in H_2 production (ELOFFY et al., 2022) These systems, however, still face limitations that currently restrict industrial-scale application, including low production efficiencies and high operational costs. Therefore, both MEC and PEMEC technologies require further optimization before implementation in large-scale applications (ELOFFY et al., 2022; GAUTAM et al., 2023; LIU et al., 2020).

Additionally, PEMEC and MEC systems are suitable only for low-molecular-weight products, such as ethanol and glycerol. A new approach for generating hydrogen from lignocellulosic biomass involves a chemical electrolysis conversion (CEC) process using aqueous polyoxometalates (POMs) as catalysts and proton carriers (LIU, et al., 2016). With this technology, biomasses such as cellulose, lignin, wood powder, and grass can react and decompose at relatively low temperatures using POM solutions (through heating or light irradiation). Hydrogen gas is then produced via electrolysis with low electricity consumption, only 16.7% of the energy required for water electrolysis. Furthermore, unlike alcohol electrolysis, no noble metal catalyst is needed at the anode, significantly reducing operational costs. This solution, however, is still at a low level of maturity and lacks examples of large-scale application.

2.3. Considerations on H_2 production from biomass

Currently, hydrogen production heavily relies on fossil sources, especially natural gas. Therefore, to achieve decarbonization goals, it is crucial to develop and improve technologies that promote low-carbon hydrogen production competitively and at large-scale.

Despite the emphasis given to hydrogen produced through water electrolysis with renewable sources, hydrogen obtained from biomass is also identified as a relevant option, particularly in contexts where abundant and competitive biomass resources related to agriculture and agroindustry are available. The valorization and use of residues from different origins contribute to environmental balance, the advancement of circular economy, and the use of renewable and low intrinsic-value sources for energy production.

The economic viability of biomass routes is influenced by a series of factors, particularly the cost of acquiring the feedstock, the suitability of the biomass for conversion into hydrogen through the chosen process, and the capital costs associated with adapting existing plants or installing new ones. It is known that larger industrial units are generally favored by economies of scale. On the other hand, in the case of a dispersed resource, increasing the scale may represent a conflict with the costs of accessing more distant biomass resources.

In addition to the conditions of the feedstock, the costs associated with hydrogen production routes via biomass depend on parameters such as temperature, pressure, and the energy required by the process, which are related to the materials that compose the equipment and the types and complexity of the catalysts used. The viability of biohydrogen production is also impacted by the additional operations that may be required in the process: the possible need for pretreatment, associated with the characteristics of the biomass and the conversion route; the concentration of the desired hydrogen produced; yield-increasing additional conversions; the separation units for product purification; catalyst recovery steps; and the incorporation of CO_2 capture and the downstream chain, for example, for carbon storage.

In general terms, there exists an indissoluble relationship between the quality of the biomass, the employed hydrogen production process, and the system's objective. Such a relationship can be expressed by the attributes of the final product in terms, for example, of the delivery conditions of H_2 and its carbon intensity. The competitiveness of biomass routes and of the hydrogen produced can also be affected by external factors such as fluctuations in fossil fuel prices; the implicit or explicit price on GHG emissions; and the presence and impact of policies for the development of biomass, low-carbon hydrogen, and associated processes such as CCS.

Several technological platforms are available for hydrogen production from biomass, such as thermochemical, biological, and electrochemical routes.

The thermochemical routes currently show higher competitiveness due to their level of technological maturity. In the Brazilian national context, there is a growing interest in reforming processes using, for example, biogas and biomethane, ethanol, or glycerol.

Brazil's biogas/biomethane potential is highly significant, given the wide variety of biomass sources available throughout the country, such as municipal solid waste, agricultural and agroindustrial residues, and animal waste. Parallelly, considering the country's high biofuel production, ethanol also stands out as a major opportunity, supported by the consolidation and strength of the biofuel industry, based on the sugarcane sector's experience and the expansion of corn ethanol plants. Finally, glycerol reforming also stands out as an attractive route because it adds value to a byproduct of the biodiesel production chain, integrating different pathways within the bioenergy industry.

From waste and field to hydrogen

Brazil stands out for its availability of residual feedstocks and agro-industrial by-products, as well as its high agricultural productivity, factors that make the country a potentially competitive producer of biohydrogen.

Globally, gasification also stands out due to its versatility in converting both dry and wet biomass, offering technical and economic advantages when using steam as the gasifying agent. The improvement of gasification reactors (conventional, plasma, and supercritical water) aims to reduce tar and char formation, as well as to prevent catalyst deactivation, thereby increasing process efficiency and H_2 yield.

Pyrolysis emerges as another thermochemical route with potential for hydrogen production through the utilization of the produced gas. Research efforts have also focused on increasing hydrogen yield from bio-oil.

The integration of CCS into hydrogen production from biomass generally represents a positive environmental impact, as it reduces the product carbon intensity. However, it introduces significant additional costs to the process. Beyond carbon capture, directing CO_2 toward productive uses is a promising alternative. For example, it can be used as a feedstock for the food or chemical industries or to produce fuels such as electrofuels, which will be discussed in Chapter 4.

Alternatively, biological routes can be employed for hydrogen production through the action of microorganisms, particularly via dark fermentation reactions of residual biomass. Electrochemical routes, in turn, can convert low-molecular-weight organic compounds into hydrogen, showing promising laboratory-scale results with lower electrical energy consumption compared to water electrolysis. However, further research development is needed for both electrochemical and biological processes to achieve technological maturity at an industrial scale and become technoeconomic viable hydrogen production routes.

3. Hydrogen use in bioenergy systems

Global hydrogen consumption increased by 2.5% from 2022 to 2023, reaching 97 Mt. Current hydrogen applications are concentrated in traditional uses, primarily petroleum refining (45% of total demand) and industrial processes, particularly for ammonia production (33% of total demand) and methanol (17% of total demand) (IEA, 2024a).

In Brazil, hydrogen consumption constantly remains near 0.5 Mt/year since 2014, except for 2020, when it decreased significantly. Petroleum refining accounts for more than two-thirds of domestic hydrogen consumption, above the global average, followed by fertilizer production and other industrial uses, notably for chemical, pulp and paper, and iron and steel sectors. It is important to emphasize that this data accounts for hydrogen use in terms of the molecule itself, excluding its derivatives. For example, although Brazil consists of a large methanol consumer, there is no significant domestic production of the chemical; therefore, it does not appear as a destination for hydrogen in the domestic scenario. Similarly, Brazil is one of the largest consumers of nitrogen fertilizers in the world, but a large portion of these products is imported – remaining absent to the national hydrogen demand.

Hydrogen is considered one of the most promising alternatives to enable decarbonization in sectors such as industry, long-distance transport, and energy storage. These new applications of H_2 grew by 40% in 2023 compared to 2022 but still represent less than 1% of global demand. However, projections for 2030 indicate a diversification in hydrogen use and a growing interest for synthetic fuels, which consume hydrogen in their production processes (IEA, 2024a).

The connection between hydrogen demand and biorefineries – considering the entire bioenergy value chain – is evident when evaluating both hydrogen traditional uses and its emerging applications, Accordingly, this chapter aims to present the main applications and opportunities for hydrogen use within the boundaries of bioenergy systems. Although not exhaustive, it demonstrates the importance of this input for the sector and how the associated demand is expected to grow as the bioenergy industry mobilizes to meet decarbonization targets, making the integration with low-carbon hydrogen a potential strategic partnership for bioenergy development.

Mutual benefit relationship

Supplying bioenergy-related processes with low-carbon hydrogen is an opportunity to develop the hydrogen market and create new avenues for bioenergy.

3.1. Scope definition: bioenergy systems

A bioenergy system can be defined as a production chain that includes agricultural production, biomass harvesting and its transportation to an industrial processing unit (plant or biorefinery), and biomass conversion into various products – primarily energy and food products. The system boundaries may also include the transport of these products to consumption centers and the utilization of residues generated throughout the chain.

Brazil has several operational bioenergy systems, being the most relevant ones associated with the production of liquid biofuels: sugarcane and corn ethanol systems, soybean and animal fat biodiesel systems, among others. Bioelectricity generation also contributes significantly to the country's energy supply, but it is typically seen as a secondary product – which is the case of sugar-energy and pulp and paper industries.

Analyzing the main bioenergy systems in Brazil, it is possible to identify stages that can use hydrogen directly or apply inputs which production currently relies on hydrogen or could rely on it in the future.

For plants and biorefineries, multiple hydrogen-based processes and inputs are used to enable the conversion of biomass into the targeted products. Currently, the main hydrogen derivative employed within bioenergy boundaries is methanol, which is used for the transesterification reaction within FAME (fatty acid methyl ester) biodiesel production. The reaction consists of a central operation in the industrial production process. Globally, nearly all methanol is produced from synthesis gas obtained from natural gas reforming. This process could be replaced by solutions that use low-carbon hydrogen.

For the future of biorefineries, production routes that use hydrogen as a direct input are expected to gain importance. The demand for sustainable aviation fuels and renewable diesel is likely to increase due to national and international transport regulations. The HEFA (Hydroprocessed Esters and Fatty Acids) technology is the most mature pathway for producing these products, and the AtJ (Alcohol-to-Jet) route is promising. Both routes include a hydrogenation step, ensuring direct demand for H_2 in biofuel production. The obtained biofuels can also be used within the bioenergy systems, particularly in the agricultural phase, including machinery and biomass transportation.

The biomass production phase is also intensive in hydrogen-derived inputs. Furthermore, it requires fuel for planting, harvesting, and transporting. Fertilizers are among the main agricultural inputs, being critical for supplying nitrogen, potassium, and phosphorus to cultivated areas. Fertilizers are considered essential to maintain the current high productivity observed in Brazil's main bioenergy crops production, such as sugarcane, corn, and soy. Globally, natural gas is the most employed feedstock for nitrogen fertilizer production, in a chain that starts with hydrogen and ammonia production. Lower-emission hydrogen production routes could potentially emerge for ammonia supply.

These opportunities for hydrogen and its derivatives in the bioenergy industry are described in more detail in this chapter, along with estimates of the volumes of hydrogen demanded by bioenergy over the next decade. An illustrative summary of these opportunities and the stages of bioenergy systems where they apply is presented in *Figure 7.*

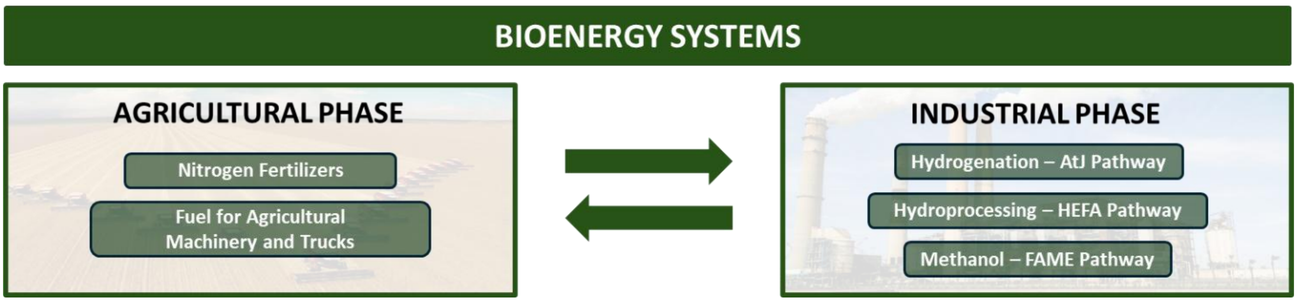


Figure 7. Opportunities for hydrogen use and derivatives in bioenergy systems.
Source: EPE

BIOENERGY AND LOW-CARBON HYDROGEN

From these opportunities, it can be generally recognized that:

1. The development of an industry capable of providing competitive low-carbon hydrogen could support the local production of essential inputs for Brazil's bioenergy systems.
2. This creates a synergy that enhances the mutual advancement of bioenergy and hydrogen, reducing costs and improving the attractiveness of the national agroindustry.
3. Particularly when low-carbon hydrogen is supplied, the emissions associated with the life cycle of Brazilian bioenergy products would be reduced, a topic further explored in Chapter 5.

3.2. Hydrogen use in biofuel production

3.2.1. Renewable diesel and sustainable aviation fuel

Renewable diesel is a renewable fuel composed of paraffinic hydrocarbons intended for use in diesel-cycle engines. It is classified as a drop-in fuel because it has properties like fossil diesel, allowing it to be used purely or blended in high proportions with fossil diesel without the need for engine modifications. Furthermore, it is also compatible with the existing fuel distribution system. Renewable diesel offers greater fuel stability than FAME, allowing for long-term storage and providing better engine performance due to a higher cetane number. In addition, it is sulfur-free and has lower impurity content (EPE, 2020).

Sustainable aviation fuels (SAF) are also blends of paraffinic hydrocarbons, generally with shorter carbon chains, and are intended for use in air transport. Like renewable diesel, SAF is considered a drop-in fuel under the blending conditions established by regulatory authorities and is compatible with the existing infrastructure for fossil-based aviation kerosene. The aviation sector has set a target to reduce carbon emissions by 50% by 2050 relative to 2005 levels, with SAF being one of the cornerstones to achieve this goal (IEA, 2019).

In Brazil, both renewable diesel and SAF are regulated and have production pathways authorized by ANP[18], as shown in Table 2. Many of these pathways are suitable for producing both fuels and require hydrogen at some stage of their production processes, as indicated in Figure 8.

[18] SAF production routes authorized by ANP are all also already approved by ASTM.

Table 2. *ANP-approved pathways for SAF and green diesel.*

SAF Pathways (ANP Res. 856/2021)	Renewable Diesel Pathways (ANP Res. 842/2021)	Acronym
Paraffinic kerosene synthesized from fatty acids and hydroprocessed esters	Hydroprocessing of vegetable oil (HVO), algae oil, microalgae oil, animal fat, and biomass fatty acids as well as bioderived hydrocarbons from the microalgae *Botryococcus braunii*	SPK-HEFA (SAF) HVO (Renewable Diesel)
Paraffinic kerosene synthesized from bioderived hydrocarbons, fatty acids, and hydroprocessed esters		SPK-HC-HEFA (SAF) HVO (Renewable Diesel)
Kerosene from hydrothermal liquefaction catalysis	Catalytic hydrothermal liquefaction of vegetable oil, algae oil, microalgae oil, animal fat, and biomass fatty acids	CHJ
Paraffinic kerosene hydroprocessed and synthesized by Fischer-Tropsch	Synthesis gas derived from biomass via Fischer-Tropsch process	FT
Paraffinic kerosene synthesized from aromatics	-	SPK/A (SAF only)
Iso-paraffins synthesized from fermented sugars and hydroprocessed	Fermentation of carbohydrates present in biomass	SIP
Paraffinic kerosene synthesized from alcohol	Oligomerization of ethyl alcohol (ethanol) or isobutyl (isobutanol) alcohol	AtJ

Source: EPE

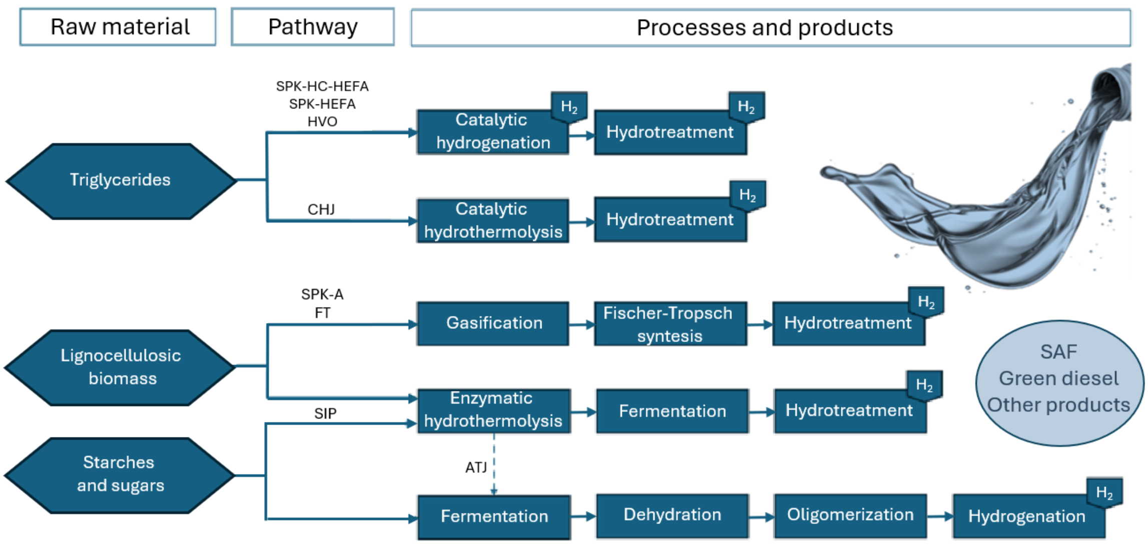


Figure 8. Main processes in SAF and green diesel production pathways.

Source: EPE from (EPE, 2020)

In the CHJ route, hydrogen is used to saturate olefins and remove residual oxygenates. In the SIP route, hydrogen is employed to hydroprocess farnesene, a $C_{15}H_{24}$ hydrocarbon obtained through sugar fermentation. The reaction with hydrogen converts farnesene into farnesane ($C_{15}H_{32}$), which is authorized for blending with aviation querosene at a maximum content of 10% (BIODIESELBR, 2021; ROITMAN, 2019).

The FT and SPK/A routes are different because SPK/A includes the addition of aromatics, which is beneficial for SAF because it helps to prevent leaks and deterioration of rubber components that seal engines. Both are synthesized through the Fischer-Tropsch process, which will be detailed in Chapter 4, covering synthetic fuels.

The SPK-HC-HEFA route employs a process like SPK-HEFA route, in which hydroprocessing is also involved, but differs in the feedstock as it uses oil derived from the microalgae *Botryococcus braunii* (EPE, 2024b).

Due to their higher technological maturity, the HEFA/HVO and AtJ routes will be described in the following sections.

HEFA/HVO

The HEFA route consists of hydroprocessing esters and fatty acids to produce biofuels, primarily renewable diesel and SAF.

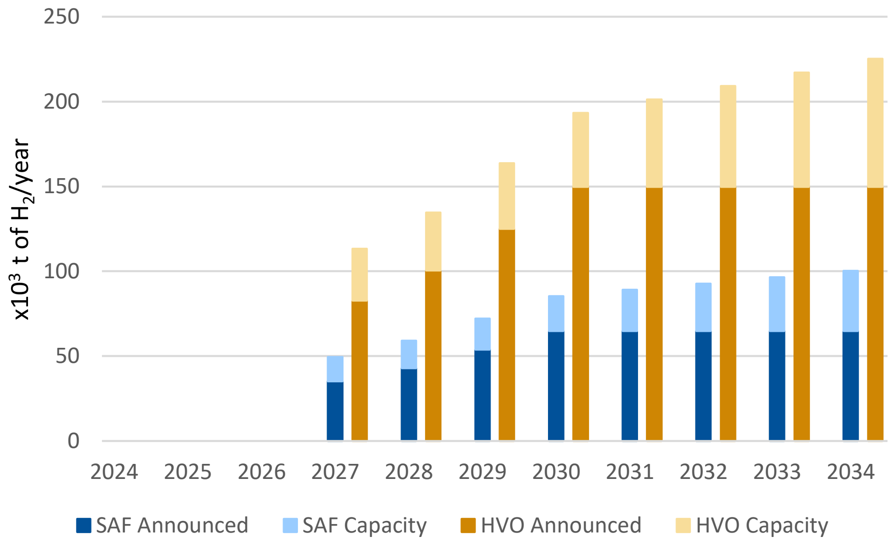
Technologically, HEFA pathway uses hydrogen to convert vegetable oils or animal fats into fuel. Hydrogen is involved in the following hydroprocessing steps, which transform the feedstock into paraffinic products: hydrodeoxygenation, where hydrogen saturates the double bonds in the triglyceride chains and removes oxygen from the molecules; cracking, where hydrogen reduces the chain length of the resulting paraffins; and hydroisomerization, which increases the content of branched components in the product (MONTEIRO, et al., 2022). Hydrogen consumption depends on the type of feedstock employed and is proportional to the concentration of double bonds and oxygen in the triglycerides.

The HEFA route is already approved by ANP for both SAF and HVO, which is the type of renewable diesel obtained through this process. The difference lies in the final step, where hydrocracking and hydroisomerization of paraffins are more intense for SAF in order to shorten and branch the carbon chains, thereby increasing the percentage of bio-kerosene molecules (PAVLENKO & KHARINA, 2018).

According to the study “Sustainable Aviation Fuels in Brazil – Future Perspectives” (EPE, 2024b), the HEFA route has demonstrated higher technological maturity when compared to other SAF-production routes and has been selected for the announced plants in Brazil up to this date. Three projects for SAF and renewable diesel production are planned for the coming years: a facility in Cubatão (SP), a future biorefinery in Manaus (AM), and a biorefinery in Bahia, scheduled to start operations in 2027, initially using soybean oil and later macauba oil as feedstock (BIODIESELBR, 2023).

Considering the annual production capacities and the feedstocks declared by each manufacturer, *Chart 1* shows the hydrogen demand required to meet the production plants' needs within the next ten years (CAPAZ et al., 2020; ZECH et al., 2018). In addition, the chart also presents the projected SAF and HVO demand that was calculated in a multicriteria assessment previously conducted by EPE (EPE, 2024b), which indicates a possible composition of SAF production plants and feedstock diversification up to 2037, increasing production capacity via the HEFA route and, consequently, hydrogen consumption. It is inferred that the national hydrogen[19] quantity required to produce biofuels via this route in 2034 could exceed 320,000 t/year[20].

Chart 1. H_2 demand for SAF and HVO via HEFA pathway – announced projects and production diversification capacity, 2024–2034.



Source: EPE.

AtJ

Although the route acronym (AtJ – Alcohol-to-Jet) refers to the use of alcohols for producing sustainable aviation fuel, it can also be applied to renewable diesel production. It is a route approved by ANP for both fuels and involves the oligomerization of short-chain alcohols to generate paraffinic hydrocarbons, using hydrogen as a reagent in the final step to saturate olefins (BIODIESELBR, 2021; NG et al., 2021).

The process begins with an intramolecular dehydration step in which the saturated alcohol is converted into an alkene. This is followed by the actual oligomerization process, where the alkene molecules (monomers) are combined to form hydrocarbons that will become renewable biofuels. After a distillation separation step, the resulting hydrocarbons undergo hydrogenation and fractionation to produce synthetic paraffinic biofuels. The renewable diesel and aviation kerosene produced are analogous to their fossil counterparts (ALBUQUERQUE, 2019; VINHADO, SOUZA, & GONÇALVES, 2019; EPE, 2020).

[19]The hydrogen demand is likely to be even higher, as projects are emerging rapidly, albeit with varying degrees of uncertainty. The Petrobras 2025–2029 Business Plan includes some of these new projects at different stages (evaluation, implementation), which may further increase hydrogen demand (PETROBRAS, 2024).

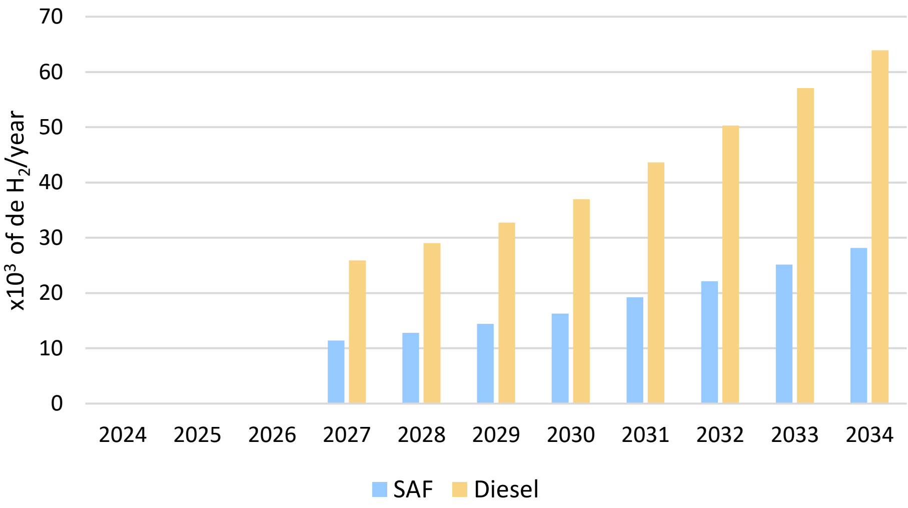
[20] Assuming that the production volumes of SAF and renewable diesel are the same for each product. Producers may, however, direct production toward the renewable fuel of greatest interest.

Currently, only two short-chain alcohols are approved by ASTM D7566-4 and ANP for use in this route: ethanol and isobutanol.

Although HEFA is expected to remain the main commercial technology in the coming years, investment in alternative technologies should be encouraged, as it allows the use of different feedstocks, supports regional development, increases production potential, enables the generation of other co-products, and ensures supply security. In this regard, the AtJ route stands out as the most mature alternative to HEFA, already presenting some industrial relevance abroad, albeit limited (DOE, 2024).

In the multi-criteria assessment published by EPE regarding SAF in Brazil, the AtJ route contributes to SAF supply using corn ethanol, 1G and 2G sugarcane ethanol, as well as potential agave ethanol (EPE, 2024b). Considering this diversity and production capacity, it is estimated that SAF and renewable diesel produced via this route in 2034 could reach nearly 2 billion liters[21], requiring 92 thousand t/year of hydrogen. The evolution of this demand can be seen in Chart 2.

Chart 2. H_2 demand for SAF and green diesel via AtJ pathway until 2034.



Source: EPE.

3.3. Methanol production

Methanol is a liquid organic alcohol at room temperature with the chemical formula CH_3OH. Its uses are diverse, ranging from the synthesis of solvents for the adhesives, flooring, and coatings industries, to its application as a fuel. In Brazil, the use of methanol as input for the transesterification reaction with triglycerides to produce FAME biodiesel stands out as its main application. FAME blending in fossil diesel is mandatory within the country (ANP, 2020; METHANOL INSTITUTE, 2024).

3.3.1 FAME Biodiesel

In 2023, Brazil consumed 7.5 billion liters of biodiesel, and it is estimated that consumption reached 9.1 billion liters in 2024, driven by the mandatory biodiesel blending percentage in fossil diesel being raised to 14% (B14) in March 2024, according to the schedule established by CNPE Resolution No. 8 of 2023 (MME, 2023).

[21] As with the HEFA pathway, it was assumed that the volume of SAF and renewable diesel produced is the same for each product. However, producers may allocate production to the product of greater interest.

Methanol is a key input for producing biodiesel via the esterification/transesterification process. Brazil imported 851.9 thousand tons of this input for biodiesel production in 2024, mostly originating from Trinidad and Tobago, Venezuela, and the United States, the largest global producer (EPE, 2024b).

3.3.2 Methanol production pathways

The currently most used pathway for producing methanol use hydrogen derived from the steam reforming of natural gas (approximately 65% of supply) or from coal gasification (approximately 35% of supply), which are, therefore, associated with high greenhouse gas emissions.

Methanol production from clean energy sources enables carbon emission reduction and can be divided into routes that generate biomethanol or e-methanol (IBERDROLA, 2023). The product's properties are the same as methanol produced from fossil feedstocks. *Figure 9* shows the main steps for producing renewable methanol.

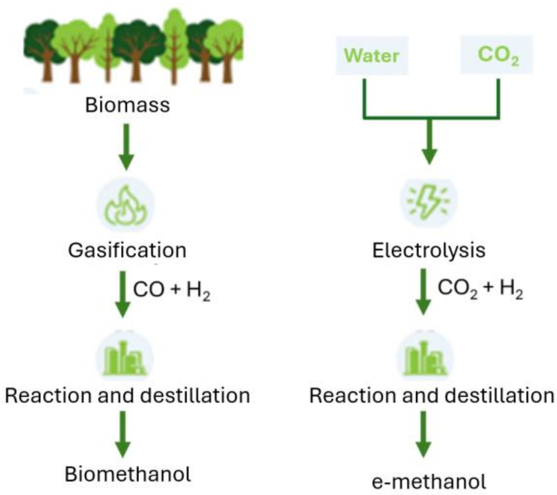


Figure 9. Low-emission methanol obtained via biomass gasification (biomethanol) and via water electrolysis (e-methanol).

Source: EPE from (IEA BIOENERGY, 2020)

Methanol production from biomass is not new. The compound was originally called "wood alcohol" because it was extracted from this material before the development of production routes based on fossil feedstocks. Today, it can be produced via syngas derived from biomass gasification, which may involve wood or other lignocellulosic or non-lignocellulosic materials, resulting in the biomethanol.

Recap

The synthesis gas is rich in H_2 and CO, and its composition is directly influenced by the physical and chemical characteristics of the biomass used.

In gasification, hydrogen is formed in situ and may require a water-gas shift (WGS) reaction step to adjust the H_2/CO ratio for methanol production, which in this case should be as close as possible to 2:1. In some instances, external hydrogen is added to achieve this ratio (IRENA, 2021).

Methanol synthesis reaction (Equation 9) is exothermic and requires reactor cooling.

$$CO + 2H_2 \rightleftharpoons CH_3OH \quad \text{Equation 9}$$

The gasification process using oil and coal as feedstock is already widely used commercially; however, its application to diverse types of biomasses is still in the early stages, and reaching a consolidated level of use requires further development. In addition, it is necessary to ensure that the used biomass has consistent and reliable logistics and supply, as well as a competitive price (IRENA, 2021).

E-methanol is produced via electrochemical processes. The simplest route comprises the catalytic hydrogenation of carbon dioxide (Equation 10) using hydrogen produced by water electrolysis. Carbon dioxide can be captured directly from the air (DAC), from industrial flue gases, or from renewable sources such as biomass combustion, biogas purification, and alcohol fermentation byproducts. This process results in fuels with lower carbon intensity when the used electricity comes from low-emission sources. A life cycle study shows that the e-methanol production process can reduce greenhouse gas emissions by 59% compared to the conventional fossil-derived process (SOLLAI et al., 2023; NEMMOUR et al., 2023).

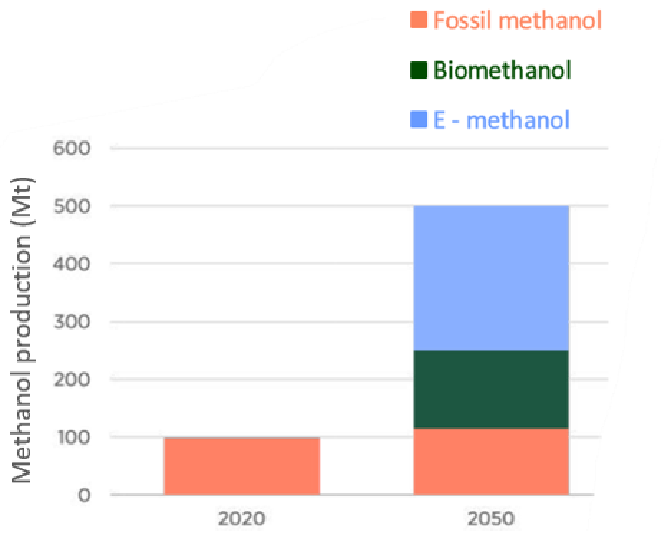
$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \qquad \text{Equation 10}$$

Another possible route consists of converting CO_2 directly to methanol. However, it is still at early development stage, although it has been tested at pilot and even industrial scale (DIETERICH, BUTTLER, HANEL, SPLIETHOFF, & FENDT, 2020). Scaling up production via this route will depend not only on plant costs but also on the availability of low-cost hydrogen and carbon dioxide. It is expected that the cost of electrolytic hydrogen will decrease over the coming years due to reductions in solar and wind energy costs, increased scale, and improvements in electrolyzers (IRENA, 2021). Another possible alternative for producing e-methanol is converting CO_2 to CO through the reverse water-gas shift (RWGS) reaction prior to alcohol synthesis. This alternative allows the use of the process represented by Equation 9, which is more established, to generate sustainable products, but it adds an additional step to the production process, resulting in higher costs and increased hydrogen consumption. Equation 9 produces a product with higher methanol content but also a higher level of impurities (DIETERICH, BUTTLER, HANEL, SPLIETHOFF, & FENDT, 2020).

When used as fuel, e-methanol falls into the category of so-called electrofuels or e-fuels, which are synthetic.

IRENA projects that methanol production could reach 500 Mt by 2050, driven by the energy transition scenario (IRENA, 2021). *Chart 3* shows projected quantities of biomethanol and e-methanol exceeding those of fossil methanol by this year.

Chart 3. Methanol production in 2020 and estimated for 2050.

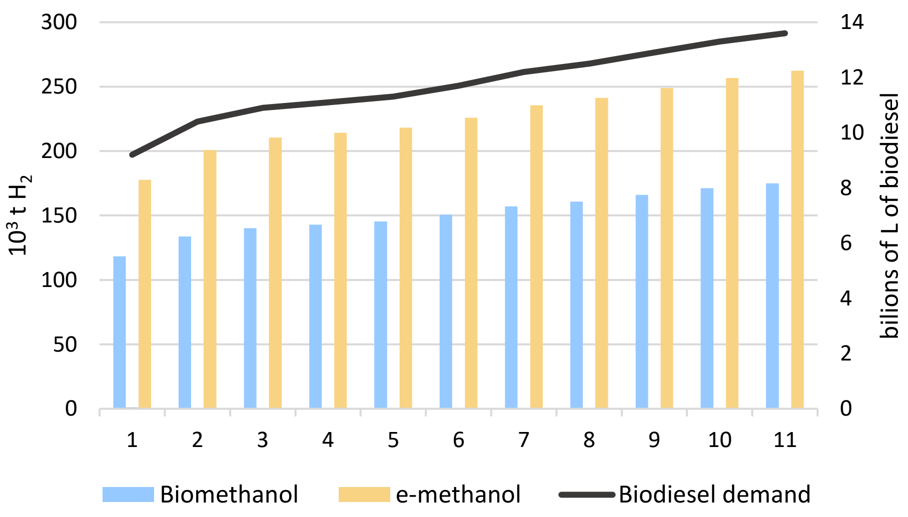


Source: based on (IRENA, 2021)

As of September 2024, 178 renewable methanol projects had been identified worldwide, estimated to produce over 29 million tons (37 billion liters) of e-methanol and biomethanol by 2030 (METHANOL INSTITUTE, 2024). There is also an expected increase in renewable methanol consumption driven by its use in maritime transport as an alternative fuel to fossil fuels. In this context, both e-methanol and biomethanol production can result in maritime fuels with up to 80% lower GHG emissions than fossil references, especially when associated, respectively, with the use of renewable energy throughout all process stages and the utilization of residual biomass (IFP Energies Nouvelles, 2025).

Considering the projected biodiesel demand in the 2034 Ten-Year Energy Expansion Plan (PDE) (EPE, 2024c), *Chart 4* shows the amount of hydrogen required to meet the methanol demand for biodiesel production in Brazil over the ten-year horizon, covering two alternatives: biomethanol production via syngas routes and e-methanol production. Given the stoichiometry of the reactions involved, the first option requires less hydrogen, which can be generated *in situ* at the plants. For e-methanol, however, there is consumption of exogenous electrolytic hydrogen.

Chart 4. In situ H_2 demand for biomethanol and added for e-methanol.



Source: EPE.

3.4. Use in fertilizer production

Fertilizer can be defined as a "mineral or organic substance, natural or synthetic, that provides one or more plant nutrients" (BRASIL, 2023). Adequate nutrient availability, and consequently the supply of fertilizers, is a fundamental element in ensuring productive and competitive large-scale agricultural production.

The three main nutrients applied in Brazil are potassium (38%), phosphorus (33%), and nitrogen (29%) (BRASIL, 2023). While phosphorus and potassium are obtained through mining, nitrogen fertilizers are produced via an energy-intensive chain.

Fertilizers and hydrogen

Ammonia synthesis consumes about one-third of the hydrogen produced worldwide.

The main use of ammonia is in the production of nitrogen fertilizers.

The importance of agriculture for Brazilian economy and the role of nutrients in ensuring high productivity elevate the strategic nature of the fertilizer supply chain for the country. However, Brazil currently imports a significant portion of its fertilizer consumption. Specifically, importing share reaches 95.7% of consumed nitrogen fertilizers. Furthermore, these imports have been increasing both in volume and expenditure, totaling 6.7 billion dollars in 2022 (EPE, 2023b).

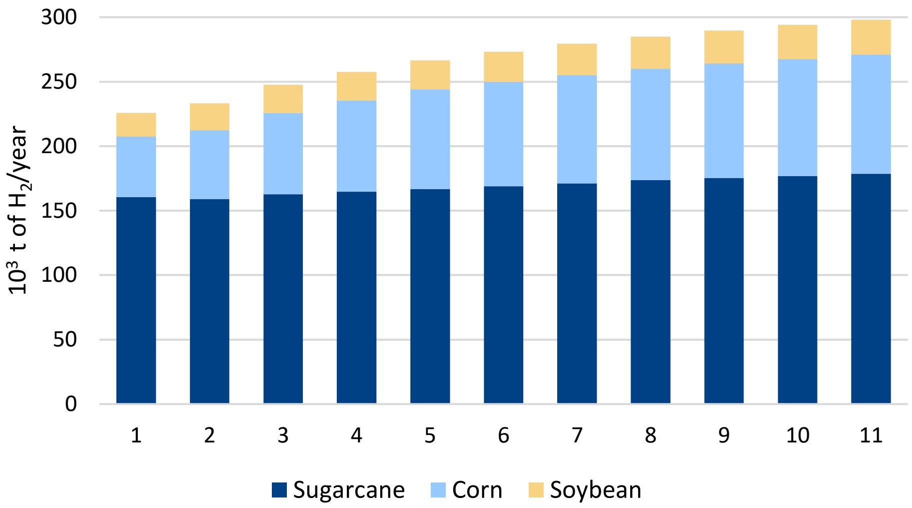
The production of nitrogen fertilizers is based on hydrogen, which reacts with atmospheric air containing 78% nitrogen (N_2). This involves the Haber-Bosch process, which results in ammonia (NH_3), the precursor of all synthetic nitrogen fertilizers.

It is estimated that ammonia production accounted for 60% of industrial hydrogen demand, which in turn absorbed 56% of global hydrogen consumption. Ammonia has various industrial applications, but about 70% of its supply is used for fertilizer synthesis (IEA, 2024a). To obtain products suitable for further transformation into final fertilizers, ammonia is typically reacted with other inputs to produce urea, ammonium nitrate, ammonium sulfate, and monoammonium and diammonium phosphates (MAP and DAP).

The growing production of biofuels in Brazil is based on agronomic systems, primarily sugarcane, maize, and soybeans. The former two provide nearly all sugar precursors for ethanol, while soybean oil accounted for 69% of the country's biodiesel feedstock in 2023 (EPE, 2024b). The total production of these three crops, including both the fraction used for biofuels and all other uses, represents more than three-quarters of the country's fertilizer consumption (GLOBALFERT, 2024).

To estimate hydrogen demand associated with fertilizers for biofuel crops, typical values for the three main crops (MATSUURA, et al., 2018) and biomass-to-biofuel conversion productivity factors were adopted to determine the demand for nitrogen fertilizers, and consequently ammonia and hydrogen, based on projected ethanol and biodiesel production according to PDE 2034. The result is shown in *Chart 5*. It can be observed that approximately 300 thousand tons per year of hydrogen are expected to be required to meet the fertilizer demand associated with bioenergy systems.

Chart 5. H_2 demand for nitrogen fertilizers from soy, corn, and sugarcane fraction for biofuel production.



Source: EPE.

3.5. Consolidation of bioenergy demand estimates

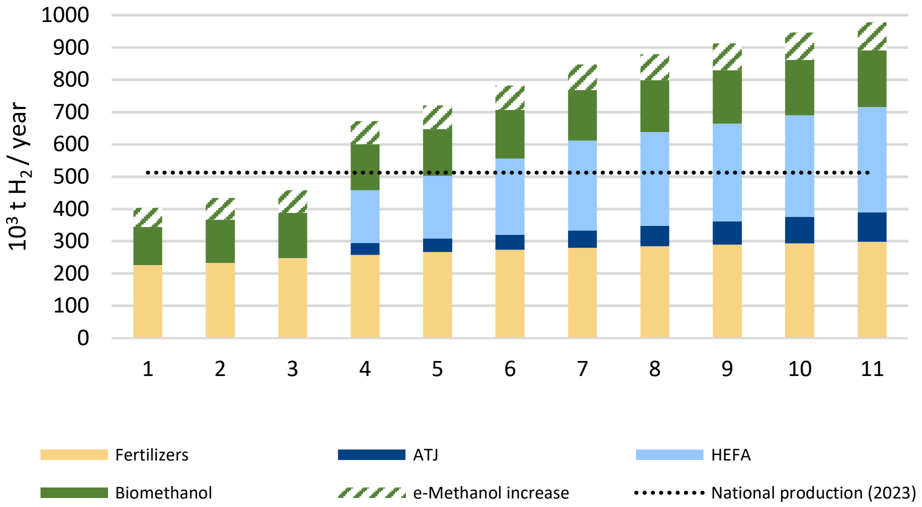
Current hydrogen production in Brazil occurs almost exclusively through natural gas steam reforming (EPE, 2022a). Hydrogen consumption, in turn, occurs mainly in refineries and fertilizer plants (87%), with local production and use. Thus, hydrogen does not currently represent a broad market product. On the contrary, it serves mainly as an intermediate input for production units that require it.

However, relatively ambitious targets for the implementation of low-carbon hydrogen have driven production in Latin America. The participation of new applications (marine, aviation, and road fuels, among others) will represent about 20% in 2035 and 60% in 2050 of the increase in hydrogen demand in the region, according to the International Energy Agency (IEA, 2024a).

The adoption of decarbonization measures using biofuels and the consequent creation of new hydrogen demand in bioenergy systems can contribute to stimulating the supply of low-emission hydrogen, providing cost reductions, improving energy security by decreasing dependence on natural gas imports, and generating export opportunities with higher added value. Hydrogen hubs have the potential to drive economies of scale and integrate supply chains, while accelerating the learning process.

Chart 6 shows the consolidated hydrogen demand in the bioenergy systems studied in this chapter compared with national hydrogen production in 2023, including all production routes (IEA, 2024a).

Chart 6. Consolidated hydrogen demand in bioenergy systems and estimated ten-year national production.



Note: For the calculation of H_2 demand for methanol, two routes were considered, with distinct H_2 volumes required to produce the same volume of methanol. Production via biomass, with an H_2:methanol ratio of 2:1 (green, filled), and e-methanol, with a 3:1 ratio, which would require an additional H_2 demand (green, hatched).

Source: EPE.

In 2024, hydrogen demand within the national bioenergy systems is mainly associated with the production of nitrogen fertilizers and methanol, which are currently supplied through imports. Over the ten-year horizon, the production of advanced fuels becomes significant, and the HEFA route emerges as the main destination for hydrogen by 2034 within the evaluated scope.

For comparison purposes, it is observed that, starting in 2027, the calculated demand[22] exceeds the amount of hydrogen produced in Brazil in 2023. In other words, the use of nitrogen fertilizers applied to bioenergy agricultural crops, the methanol used in biodiesel production, and the hydrogen requirements in biorefineries to produce new biofuels make hydrogen demand associated with bioenergy quite significant.

Thus, the interest of this sector in reducing the carbon intensity of biofuels and their co-products, particularly through access to low-carbon inputs may play a significant role in driving the development of national hydrogen value chains. As presented in Chapter 2, bioenergy resources themselves, together with other low-carbon pathways such as electrolysis using renewable sources, are alternatives for building these value chains and for meeting the national demand for hydrogen and its derivatives.

Therefore, it is evident that the bioenergy sector can contribute to ensuring that resources, incentives, and ultimately hydrogen production are prioritized for local use, with the objective of promoting decarbonization and improving the competitiveness of Brazilian production.

[22] It is important to note that this analysis is limited solely to hydrogen consumption within bioenergy systems. Significant traditional uses, such as in petroleum refining, will continue to exist in the coming years but were not included in this assessment.

3.6. Other possibilities

This section presents two additional uses of hydrogen associated with bioenergy systems that may be implemented. Unlike the opportunities presented so far, however, these uses do not have sufficient materiality for quantitative demand estimates.

3.6.1 Direct and indirect use as a fuel

Trucks and other heavy road vehicles are mostly powered by diesel. However, with the decarbonization targets for freight transport, alternative fuels are being explored, and hydrogen has emerged as a potential long-term option. The development of hydrogen-powered truck drivetrains is currently in the testing phase, but challenges remain in terms of costs and logistics, particularly regarding transmission technology (DAF, 2024).

Two options are being studied for the use of hydrogen in heavy road transport: direct use as a fuel in combustion engines or through a fuel cell that uses hydrogen to generate electricity, that in turn powers an electric motor (DAF, 2024).

Major manufacturers are focusing on these technologies, with truck development and road testing projected between 2025 and 2026, including hydrogen produced from ethanol in Brazil (ESTADAO, 2024; AUTOESPORTE, 2024). Additionally, hydrogen could be considered a potential alternative fuel for agricultural machinery, with a prototype tractor currently on display (FENDT, 2023).

Beyond the direct use of hydrogen as a fuel, an emerging possibility is the use of synthetic fuels for these vehicles, which consume hydrogen as an intermediate.

3.6.2 Biogas enrichment to biomethane

Biogas is the raw product of anaerobic digestion, composed primarily of methane (CH_4, 50-70%) and carbon dioxide (CO_2, 30-50%). Purification of biogas produces biomethane, a biofuel whose quality is regulated by the ANP. Compliance with the requirements established by the agency makes it interchangeable with natural gas, allowing, for instance, the injection of biomethane into the pipeline network.

The typical biomethane production process relies on technologies designed to separate the CO_2 present in biogas, increasing the CH_4 concentration to levels established by regulation.

An alternative to traditional purification solutions is the reaction of hydrogen with biogas, particularly with the CO_2 it contains. This is methanation, a process represented by Equation 11 (MURPHY, RUSMANIS, GRAY, & O'SHEA, 2024) aimed at producing more CH_4 and characterized as the inverse of the overall methane steam reforming reaction (including WGS).

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + H_2O \qquad \text{Equation 11}$$

In the context of biogas plants, methanation serves two purposes. While it increases the supply of biomethane, the process also purifies the biogas by enriching it in CH_4. This solution presents several opportunities:

- Scale-up: In many biomethane projects, product logistics can be hindered by the small scale of plants based on organic waste; additional production can improve access to infrastructure and markets.
- Avoid CO_2 separation: With the consumption of CO_2 in the reaction with hydrogen, the product becomes rich in CH_4, reducing costs associated with conventional biogas purification steps, which are significant.
- Use existing infrastructure: Additional methane production enables access to infrastructure built for natural gas, which may not be available for hydrogen.
- Valorize biogenic CO_2[23]: Instead of releasing it into the atmosphere, as is common in biomethane plants, carbon is valorized through additional energy production.

Regarding biogenic CO2, its importance has been increasingly highlighted in various studies, both for utilization and storage purposes[24], aiming at negative emissions. However, there are limitations in practical application, particularly at the scale of biogas plants. Direct use of CO_2 at its production site can develop this concept without incurring high purification costs for CO_2 itself or requiring its transport to a demand point.

On the other hand, it is important to note the economic challenge of methanation, given that hydrogen tends to be a high-cost product, with a value greater than methane.

The combination of hydrogen with biogas may also favor the production of synthetic fuels, a topic that will be addressed in Chapter 4.

BEYOND THE ENERGY SECTOR: APPLICATION IN CHEMICALS

The production pathways for bioenergy and biofuels can be associated with the generation of various other valuable molecules for a wide range of applications, such as polymer and pharmaceutical precursors. Within these applications, hydrogen appears as a key input in transformation processes, particularly in sugar hydrogenation.

In terms of volume, the sugar platform is considered the largest to produce biomass-based chemicals. In addition to traditional processes that extract glucose and fructose from sugarcane sucrose or glucose from corn starch hydrolysis, advanced processes using lignocellulosic feedstocks allow the production of glucose from cellulose and other sugars from hemicellulose. Concurrently with sugars, lignin is also obtained during the processing of lignocellulosic biomass.

Hydrogenation of sugars results in polyols, which are used in food sweeteners and rubber foam. Hydrogenation of lignin produces bioaromatics, which can serve as additives in industries such as aviation.

Thus, the availability of H_2 in biorefineries can open new opportunities for processes and products, creating new markets with the potential for higher added value (IEA BIOENERGY, 2020).

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[23] Biogenic CO_2 is defined as that generated from biomass, whether through combustion, fermentation, or any other conversion process (EMAIS ENERGIA, 2024; CMS, 2024).

[24] Storage refers to Bio-CCS / BECCS (Bioenergy with carbon capture and storage). This concept is developed in Chapter 4.

4. Synthetic fuels

A particular use of hydrogen – including biomass-derived hydrogen – is the production of synthetic fuels, which can be defined as artificially obtained hydrocarbons[25] that can be used in engines and existing infrastructure without significant modifications; that is, drop-in fuels (EPE, 2023a).

These fuels can be classified into two categories according to the source of hydrogen and carbon used for synthesis: e-fuels and biomass-derived synthetic fuels, also known as synthetic biofuels. A non-exhaustive flowchart of possible synthetic fuel production processes is presented in Figure 10.

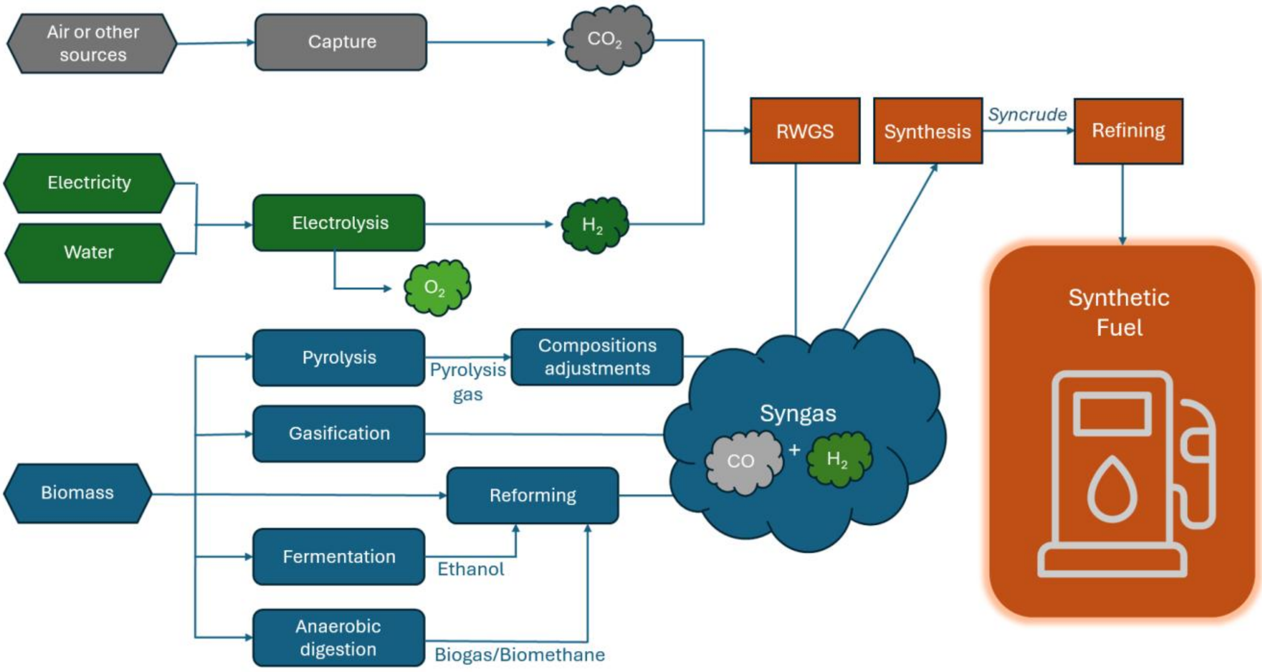


Figure 10. Pathways for synthetic fuel production from biomass and electrofuels[26].
Source: EPE from (IEA, 2024e).

There are several ways in which biomass can contribute to the production of synthetic fuels, including:

- Biomass as raw material:
  - Biomass can be used in thermochemical processes to produce synthetic biofuels (detailed in Section 4.1), as the main source of both carbon and hydrogen for hydrocarbon formation;
  - Biogenic carbon (derived from biomass) can be combined with hydrogen from another origin. In this case, low-carbon hydrogen sources are preferred, such as electrolytic hydrogen to produce e-fuels (detailed in Section 4.2) or natural hydrogen.
- Biomass as energy source: Biomass can also be used to supply electricity via thermoelectric generation for hydrogen production and, subsequently, for e-fuels.

[25] Other molecules can also be considered synthetic fuels, such as ammonia and methanol; however, this chapter will be limited to drop-in hydrocarbons.

[26] RWGS = Reverse Water-Gas Shift (13).

4.1 Synthetic biofuels

For limiting the scope of this Chapter 4, only fuel production routes that use synthesis gas[27] as an intermediate compound were addressed here.

Currently, the most studied technologies for producing synthetic biofuels via synthesis gas are thermochemical routes (SWAIN, DAS, & NAIK, 2011). The production processes are those presented in Chapter 2 for hydrogen production, with the difference that there is no hydrogen separation step. Instead, the carbon present in the biomass is also utilized to form the hydrocarbon chain of the desired fuel (LEE, SEIDL, & MEYER, 2021).

In the production of synthetic biofuels, thermochemical reforming or gasification routes serve to break down biomass molecules to form synthesis gas, subsequently used in the Fischer-Tropsch reaction. This conversion can also be referred to as BtL ("biomass to liquid"), which produces various types of synthetic hydrocarbons, including fuels like diesel and gasoline. Fischer-Tropsch synthesis is one of the main methods for producing synthetic fuels, consisting of converting synthesis gas into fuels analogous to those of fossil origin through a catalyzed process (PROQR, 2021; ROYAL SOCIETY, 2019).

Biomass for synthetic fuel production

Biomass typically contains carbon, hydrogen, and oxygen, providing the necessary constituents for the formation of synthesis gas and synthetic fuels.

The presence of H_2 and CO or CO_2 molecules within the process itself represents an advantage of this production route compared to other options, such as electrolysis.

Since the H_2/CO ratio obtained from biomass may not be optimal for the process considering its intended purpose (for example, the type of fuel to be produced), hydrogen from an external source can be added to optimize it (KAPTEIJN & MOULIJN, 2022; SPATH & DAYTON, 2003).

[27] There are other routes for producing drop-in hydrocarbons from biomass, such as HVO/HEFA and AtJ, which also use H_2 as a reagent in certain process steps, as described in Chapter 3. These routes are not included in this chapter because they rely on modifying complex structures, such as vegetable oils and alcohols, which already contain C-H and C-C bonds typical of the hydrocarbons to be produced. According to some classifications, these fuels could also be considered synthetic biofuels. However, there is no consensus regarding the exact definition of the concept. In the case of synthesis gas as an intermediate, the feedstock molecules consist of CO and H_2, and the "construction" of the hydrocarbon occurs through the formation of C-H and C-C bonds.

FISCHER-TROPSCH SYNTHESIS

The Fischer-Tropsch reaction enables the growth of the carbon chain through sequential CH_2 addition and can be generically described by Equation (A), followed by CO_2 generation via the Water-Gas Shift (WGS) reaction (B). The overall reaction is represented by Equation (C).

Fischer-Tropsch reaction:

$$nCO + 2nH_2 \rightarrow -(-CH_2-)_n- + nH_2O \qquad (A)$$

$$nCO + nH_2O \rightarrow nH_2 + nCO_2 \qquad (WGS) \qquad (B)$$

$$2nCO + nH_2 \rightarrow -(-CH_2-)_n- + nCO_2 \qquad (C)$$

The final length of the carbon chains is determined by the chain growth probability, which is inversely proportional to the H_2/CO ratio and the temperature. To obtain heavier products, the H_2/CO ratio should approach 2:1 to avoid unwanted byproducts. A high ratio can increase methane production, while a very low ratio tends to produce longer chains but may generate more coke if the hydrogen concentration is too low (KLERK, 2011). Specific equations and proportions are provided in Table 3.

Table 3. ***H_2-to-CO usage ratio in different Fischer–Tropsch reactions.***

Product	Equation	H_2:CO usage ratio
Methane	$CO + 3\ H_2 \rightarrow CH_4 + H_2O$	3
Paraffins	$n\ CO + (2n+1)\ H_2 \rightarrow C_nH_{2n+2} + n\ H_2O$	(2n+1)/n
Olefins	$n\ CO + 2n\ H_2 \rightarrow C_nH_{2n} + n\ H_2O$	2
Alcohols	$n\ CO + 2n\ H_2 \rightarrow C_nH_{2n+1}OH + (n-1)\ H_2O$	2
Aldehydes	$n\ CO + 2n\ H_2 \rightarrow C_nH_{2n}O + (n-1)\ H_2O$	(2n-1)/n
Acids	$n\ CO + 2n\ H_2 \rightarrow C_{n-1}H_{2n-1}COOH + (n-2)\ H_2O$	(2n-2)/n

Source: (KLERK, 2011)

The resulting hydrocarbon mixture can be referred to as synthetic crude oil, or "syncrude", with product selectivity influenced by process conditions such as temperature, syngas composition, and catalyst composition, among others (LU & YEE, 2007). Temperatures can range from 200 to 240°C for low-temperature processes or 300 to 350°C for high-temperature processes. Operating pressures are typically between 10 and 40 bar (SPATH & DAYTON, 2003; MUKOMA, HILDEBRANDT, & GLASSER, 2006).

The use of catalysts impels a high syngas purity to minimize catalyst deactivation due to poisoning. Limits are set for sulfur, halides, ammonia, NOx, and hydrogen cyanide (SPATH & DAYTON, 2003).

Synthetic crude production from biogas stands out as an alternative route for producing synthetic biofuels. The first Brazilian pilot plant employing this technology was installed in Paraná State, using catalyzed dry reforming of the feedstock, according to Equation 3, to obtain syncrude. Biogas dry reforming occurs at atmospheric pressure and temperatures between 600 and 900°C and requires catalysts that are efficient, stable, and low-cost. The main challenge of this process is preventing catalyst deactivation due to coke deposition on the surface. After reforming, the resulting syngas undergoes a Fischer-Tropsch reaction to produce syncrude, which is then processed to separate various products, similarly to conventional petroleum (OLIVEIRA, et al., 2021). All these steps comprise the so-called Gas-to-Liquid (GtL)[28] process and may require the addition of exogenous hydrogen, which, in this plant, will be electrolytic. The goal is for this synthetic crude to be refined and converted into SAF (ITAIPU, 2024).

The Fischer-Tropsch process offers significant flexibility to produce fuels and chemical products, ensuring compliance with technical specifications like those of petroleum derivatives. This process can also supply higher value-added chains, such as food, cosmetics, and pharmaceuticals, as well as create base molecules for the petrochemical industry (RAMOS, et al., 2011; SWAIN, DAS, & NAIK, 2011).

4.2 Electrofuels

E-fuels are a class of synthetic fuels produced by combining carbon dioxide (CO_2) or carbon monoxide (CO) with hydrogen (H_2) obtained from water electrolysis (EPE, 2023a). E-fuels can be produced via the Fischer-Tropsch reaction, as described previously. In this case, CO_2 must be converted to CO to generate syngas, which can be achieved through RWGS (reverse water-gas shift)[29] - Equation 12 - or by directly producing syngas in high-temperature co-electrolysis operations (a technology with maturity level estimated at TRL = 6) (IEA, 2024e).

E-fuels: Brazil's leading role

Brazil emerges as a potential producer of low-carbon e-fuels due to the assets of its power system, which has a high share of renewables and favorable conditions for their expansion, combined with the availability of biogenic CO_2 (originating from biomass, regardless of the associated industrial process) at competitive costs.

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \qquad \text{Equation 12}$$

E-fuels incorporate the concept of Power-to-X (PtX), which refers to technologies that convert electrical energy into other forms of energy (RSB, 2023), such as fuels. They are particularly useful in systems with high renewable energy generation, as they utilize excess electricity for purposes beyond power supply. For liquid fuels, PtX technologies are also referred to as power-to-fuel or power-to-liquid, and for gaseous fuels, as power-to-gas.

[28] Gas-to-liquid (GtL) processes are also used for converting natural gas into liquid fuels. In this case, steam reforming of methane (Equation 2) is employed instead of dry reforming (Equation 3), which is used for biogas due to the higher CO_2 concentration in the renewable product. Although biogas is a biologically derived product, the term biomass-to-liquid (BtL) is not used here, as it is typically reserved for processes that produce synthesis gas from solid biomass.

[29] This process is exactly the reverse of that shown in Equation 1.

Brazil can become an important player for the PtX industry due to the potential of biomass as a source of biogenic CO_2 (EMAIS ENERGIA, 2024) and because of its highly renewable electricity matrix. In some definitions, these fuels are classified as e-fuels only if the electricity used for synthesis comes from renewable sources (PALYS & DAOUTIDIS, 2022; ACATECH, 2016).

A similar concept is that of renewable fuels of non-biological origin (RFNBO), mentioned by the European Union. These are synthetic fuels obtained from hydrogen coming from renewable energy (excluding biomass) combined with CO_2 derived from non-renewable or natural sources, such as fossil fuels or direct air capture. Since electricity is an input with significant impact on the cost and carbon intensity of RFNBOs, synthesis can be prioritized in periods and/or regions with excess local electricity production (EUROPEAN COMMISSION, 2022). RFNBOs can be classified as e-fuels if electricity is used as an energy source, although not all e-fuels are RFNBOs (RSB, 2023).

With the increase of renewable sources in the energy sector, other sectors need to adapt quickly in areas such as energy efficiency, direct use of renewable energy, and infrastructure. Combining different energy sources with specific demands is a strategy that has been applied for years in energy systems, but the introduction of sector coupling leverages the potential to create strategies and technologies that increase the flexibility of these systems by integrating them with renewables, aiming to achieve 100% use of renewable energy. Some examples are the direct use of renewable electricity for cooking and its indirect uses such as hydrogen, biofuels, and e-fuels production (IRENA, 2022b). In this context, e-fuels link electricity and fuels.

The use of electrolytic hydrogen for fuel production is not new, as it has been applied since the first half of the 20th century for ammonia production. However, these early plants were discontinued due to the more competitive economics of using fossil fuels. Nevertheless, the current need for decarbonization coupled with the availability of renewable sources led to the conduction of new tests for fuel production. Promising results were obtained, even though most are still at the demonstration scale (IEA, 2024e).

The main factors affecting water electrolysis for hydrogen production are electrolyzer technology and the required energy. Various approaches have been studied to make these systems more efficient and less costly (IEA, 2024e). Regarding energy, it is estimated that 70 to 80% of the cost of electrolytic hydrogen production is determined by the electricity price, and Brazil shows competitive potential due to the possibility of using high amortization hydroelectricity, solar and wind energy, whose prices have been decreasing over the years, as well as bioelectricity (EMAIS ENERGIA, 2024).

When a low-emission electricity source is used, such as nuclear or renewable, and assuming zero emissions in the life cycle of the carbon source used (biogenic CO_2), e-fuel emissions can be 75–98% lower than those of the fossil fuels they mimic (IEA, 2024e).

All e-fuels, except ammonia, require a carbon source for their production. The cost of the CO_2 used is inversely proportional to its concentration. The main renewable options are presented in *Figure 11*. It should be noted that the cost of direct air capture of CO_2 can be up to ten times higher than that biogenic CO_2.

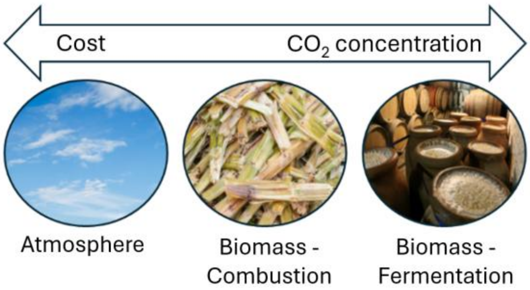


Figure 11. Carbon sources for e-fuel production.
Source: EPE from (IEA, 2024e)

Contribution of biomass to electrofuels production

The production of electrofuels can benefit from biogenic CO_2 sources, which have relatively low costs and higher environmental value.

In turn, the production of electrolytic hydrogen can be based, directly or indirectly through the electrical system, on the supply of renewable energy from biomass.

Thus, ethanol, biogas, and biomass plants emerge as options to supply the demand for low-cost renewable CO_2. A study indicates that these feedstocks are viable possibilities for South America and the United States of America due to the large number of installed plants (MAERSK CENTER, 2024). In this context, Brazil presents an important competitive advantage given the availability of various point sources of biogenic CO_2. The CO_2 potential deriving from ethanol fermentation is estimated at around 26 million tons of CO_2 per year in 2024, possibly reaching 35 million tons of CO_2 per year in 2034 (EPE, 2024c). This CO_2 is also notable for its very high purity, which facilitates subsequent gas utilization processes.

Furthermore, while the use of CO_2 to produce electrofuels may consist of an advantageous pathway in Brazil from a national perspective, from a firm level carbon capture and utilization also stands out as a technology that leverages new business model for industries that produce carbon dioxide, as these players may generate additional revenue from a byproduct. Also, in cases where synthetic fuels are obtained in parallel with carbon capture and storage – BECCS/BioCCS, BioEnergy with Carbon Capture and Storage – it is possible to achieve carbon-neutral or even carbon-negative emissions (EPE, 2023d).

A special category of synthetics

The possibility of combining e-fuel production routes with those for synthetic biofuels can create a hybrid e-biofuel process, referred to in the literature as PBtL (power and biomass to liquids).

The use of biogenic CO_2 is the most evident synergy between biofuel and electrofuel production processes, but there are still other ways to combine these two pathways.

In the production of synthetic biofuels, part of the carbon may need to be removed from the process because the carbon-to-hydrogen ratio present in biomass is high, and therefore there is not enough hydrogen in the synthesis gas to convert all the carbon into fuel. However, production can be maximized if external hydrogen, such as electrolytic hydrogen, is added to react with the excess carbon in the medium (HANNULA, 2016). In this case, an e-biofuel would be obtained (IEA, 2024e).

In addition, the oxygen produced during water electrolysis for hydrogen production can be used in the gasification process, avoiding the need for investment in a cryogenic air separation unit if pure O_2 is desired as the gasifying agent, taking advantage of its associated benefits. The heat, a byproduct of electrolysis, can be used to dry the biomass, a pretreatment usually required downstream of gasification. The diagram in *Figure 12* shows how this synergy takes place.

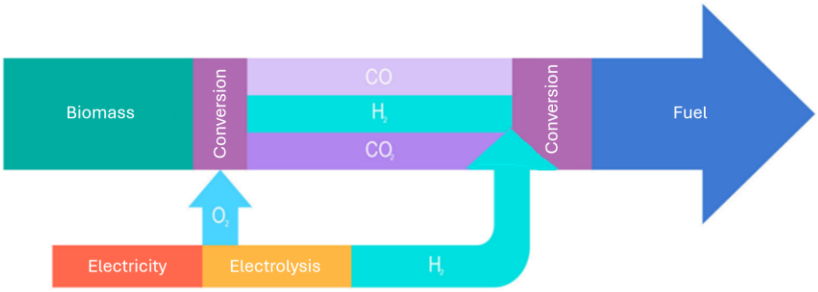


Figure 12. Representative scheme of e-biofuel production.
Source: from (IEA, 2024e)

The oxygen generated as a byproduct of electrolysis can also be used in other applications, among which oxy-combustion stands out. It is the combustion carried out with oxygen, which reaches higher temperatures and produces gas effluents richer in CO_2, facilitating capture. In another synergy with bioenergy, applying oxygen to biomass combustion can improve the feasibility of obtaining biogenic CO_2 for utilization or permanent storage.

The production cost of e-fuels can be 3 to 5 times higher than that of fossil equivalents due to the low maturity of the technologies involved in production and conversion losses (UDOP, 2024). For e-fuels to become more economically viable, enabling actions are necessary, such as regulatory incentives, selection of locations with high renewable energy availability, proximity to consumer markets, and maturity of industrial processes (AGORA & FRONTIER ECONOMICS, 2018; CONCAWE, 2020).

Another form of decarbonizing the transport sector is direct electrification. This case emerges as a viable alternative especially for passenger vehicles, small trucks, and ships on short and predictable routes, such as ferry operations. For these applications, direct electrification can be prioritized, given that the overall energy efficiency of using electricity in vehicle batteries is 4 to 6 times higher than that of e-fuels in combustion engines, due to conversion inefficiencies[30] (CONCAWE, 2020). However, regarding heavy and/or long-distance transport, electrification is challenging with current technologies due to high costs, low range, and/or high battery weight and space requirements, as well as long charging times. Therefore, the use of e-fuels and biofuels, including synthetic ones, appears as an option for these sectors to also achieve their decarbonization targets (UDOP, 2024).

Relatively to road transport, EPE prepared the Technical Note “Alternative Powertrains in Trucks and Buses in Brazil,” which evaluates potential trajectories for the adoption of alternative powertrain technologies in the Brazilian fleet of these vehicles, identifying the main barriers and the advantages associated with each technological solution (EPE, 2023c).

4.3 Synthetic fuels demand

The interest in synthetic fuels is mainly justified by their renewability and by the potential to produce them with low carbon intensity, characterizing them as prominent solution for emissions reduction by fossil fuel replacement. To this end, it is necessary to ensure that biomass/hydrogen

[30] The overall efficiency of electrofuels may include the energy losses observed in the following stages: (a) conversion of electricity into hydrogen in electrolyzers and CO_2 capture, (b) conversion of hydrogen and CO_2 into electrofuels, (c) conversion of electrofuels into mechanical energy in vehicle engines.

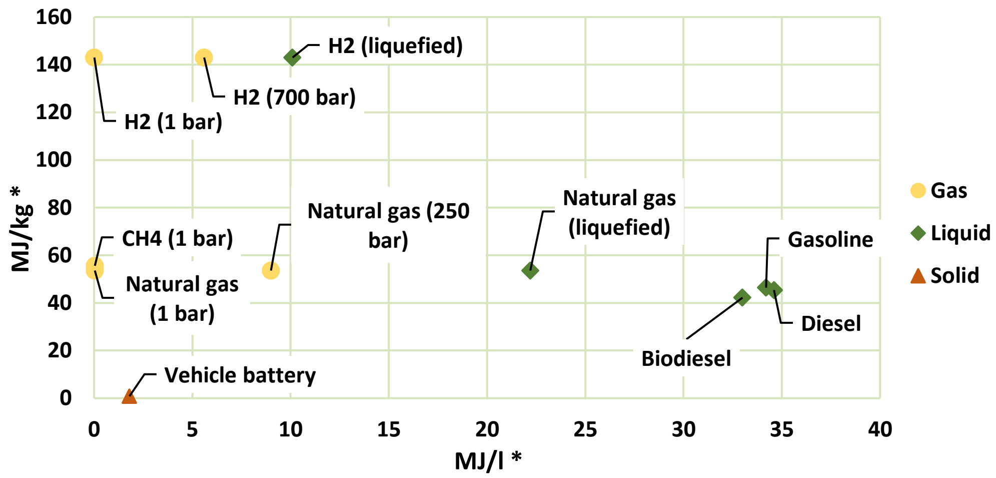
and CO_2 raw materials are obtained in compliance with low-emission requirements and broader sustainability criteria.

Since synthetic fuels are produced using some technologies and value chains which are still under development, they still present high production costs, which magnitude varies for distinct technologies. It is expected that synthetic biofuels will generally present lower costs than electrofuels in the coming years, although both are expected to have higher prices than petroleum derivatives (ROYAL SOCIETY, 2019) and conventional biofuels.

Even so, different studies indicate that the contribution of synthetic fuels to energy supply will be significant, especially in the transport sector (AGORA & FRONTIER ECONOMICS, 2018; MALINS, C., 2017; IEA, 2024a.

This is primarily due to the difficulty of directly electrifying some transportation modes and vehicles and the longevity of existing assets, especially aircraft, ships, and heavy-duty trucks used in long-distance routes, which will continue to demand energy delivered in a similar form to the current liquid fossil fuels. In these sectors, maximizing useful space, ensuring high autonomy, and refueling speed are essential factors, which indicates the need for fuels with high energy density, a characteristic associated with hydrocarbons, as shown in *Chart 7* (CARVALHO et al., 2021).

Chart 7. Energy density comparison of selected fuels.



*Note: Gravimetric energy density (MJ/kg) is also referred to as specific energy, and volumetric energy density (MJ/l) as energy density.

Source: EPE based on (MAZLOOMI & GOMES, 2012; CAO, ZHANG, & LI, 2020).

Therefore, sustainable fuels, especially drop-in fuels, hold fundamental importance for achieving decarbonization at the pace required to meet global targets. Synthetic fuels are part of this group, adding supply volume the limited potential of the already established routes for conventional biofuels – such as those produced from vegetable oils or sugars and carbohydrates, for example. *Figure 14.* illustrates the series of factors that may drive the demand for synthetic fuels.

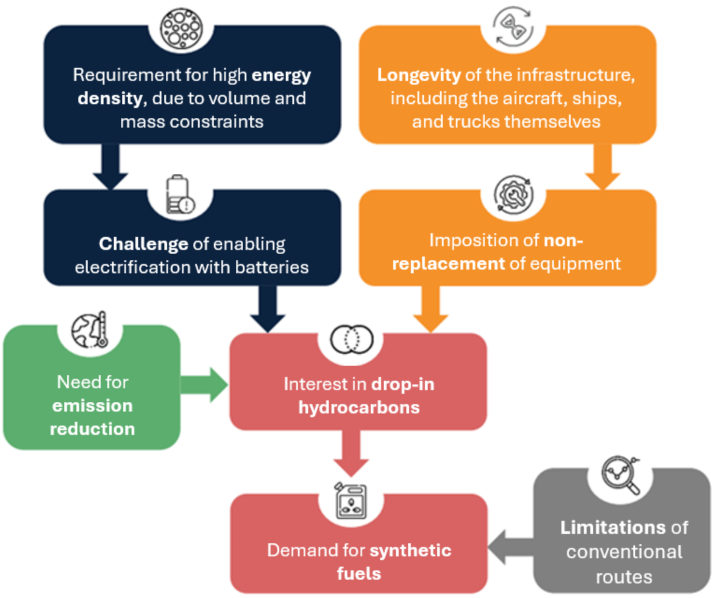


Figure 13. Requirements and limitations leading to the need for synthetic fuels in the transport sector.
Source: (EPE, 2024c).

Thus, the diversification of feedstocks is an important part of the motivation to produce synthetic fuels. The routes that involve synthesis gas encompass various types of biomasses, such as lignocellulosic materials, which are attractive alternatives due to their lower market value. Other favorable aspects of lignocellulosic biomass for synthetic biofuels are its widespread availability across different geographic regions, its productivity – which can be higher in terms of carbon yield per area – and its processing characteristics, which allows aiming for the complete conversion of biomass into the desired product[31]. In other words, despite the need for adaptation to the specific type of lignocellulosic biomass in each biorefinery, almost any existing agricultural crop can be used, with greater biomass availability per hectare, and the conversion can be optimized, creating a potential for universalization of sustainable biofuel production. By using residual biomass, there is an added potential for value creation of such products and a new market opportunity for the agricultural sector (SWAIN, DAS, & NAIK, 2011).

Regarding the advantages of e-fuels, one challenge lies in the logistics of hydrogen (H_2) generated from low-carbon electricity. The alternative of building pure hydrogen pipelines presents high associated costs and brings technical concerns related to steel and weld embrittlement, leakage control, and compressor operation. Furthermore, tightness is a key issue because hydrogen is highly flammable. Synthetic fuels are therefore a more viable option for transporting hydrogen, due to their high energy density, safety aspects, and their compatibility with the already established infrastructure for petroleum-derived fuels (MALINS, C., 2017).

[31] In the case of soybeans, for example, even considering only the grain, only about 20% of the mass content is oil, and during conversion to biodiesel, part of the carbon is "lost" as a coproduct in glycerin. In the case of sugarcane ethanol, the sugars make up a minor portion of the carbon content of the biomass, and part is released as CO_2 during the fermentation step.

The blending of hydrogen into existing natural gas networks also faces significant barriers. Concerns revolve around the additional costs associated with gas separation, modifications in monitoring and integrity management practices, and potential pipeline replacements, which may be required if a high hydrogen percentage[32] is introduced into the mixture. For storage, large volumes are needed in addition to high costs and the limited maturity of available commercial techniques. It is estimated that a hydrogen content between 5% and 15% could be feasible without significantly increasing risks, while maintaining the volumetric heating value within the limits established by Brazilian regulations (EPE, 2022b).

In the case of ship refueling, the option of using H_2 in fuel cells for propulsion would have to overcome issues such as engine adaptation, high flammability of H_2, and elevated costs (CARVALHO et al., 2021).

In addition, it is noteworthy that synthetic fuels have other environmental advantages over petroleum-derived fuels, as they contain lower levels of sulfur and nitrogen – SO_X and NO_X, are free of heavy metals, and have lower aromatic content, reduced particulate matter generation, and lower CO_2 emissions during combustion, representing improvements in safety and occupational health (RAMOS, et al., 2011; SMAGALA et al, 2013; SWAIN, DAS, & NAIK, 2011).

For all these reasons, other sectors can also benefit from the use of synthetic fuels, as shown in Table 4. Industries, power generation, and thermal energy applications stand out as potential users in their decarbonization processes (CONCAWE, 2020).

Table 4. ***Potential uses of synthetic fuels in different economic sectors.***

Sector	Uses	Motivation
Transport	Aviation, maritime, heavy-duty vehicles covering long distances.	Hard-to-abate sector, where electrification is hindered due to space, weight, and refueling time constraints, the need for high autonomy, the longevity of existing infrastructure, and the costs of its replacement.
Industry	Production of organic chemical compounds.	Substitution of petroleum, natural gas, and their derivatives currently used as feedstocks in the petrochemical industry.
Power Generation	Long-term storage required for periods of renewable generation deficit, due to seasonal and interannual variations. Storable energy for isolated systems.	While batteries are useful for shifting renewable generation over short periods, long-term storage of large amounts of energy has fewer reliable and cost-effective options, depending on sustainable fuels in a low-emission future.
Heating	High-temperature thermal demands in hard-to-decarbonize applications, and low-temperature uses, including in hybrid systems.	Situations where it is not possible to use heat pumps powered by renewable energy.

Source: EPE based on (AGORA & FRONTIER ECONOMICS, 2018).

[32] The sensitivity to hydrogen blending varies according to the type of natural gas infrastructure, with adjustments potentially allowing for higher blending levels. Some countries set blending limits in natural gas networks, with higher values permitted under special conditions (EPE, 2022b).

Therefore, in addition to the transport sector, which emerges as the main destination for synthetic fuels, it is noteworthy that demand for these energetic vectors can extend to other sectors and contribute to increased scale and dissemination of these pathways in the energy transition.

5. Carbon intensity and certification

5.1. Concepts and application

One of the main drivers for hydrogen adoption is the absence of carbon in its composition, which prevents CO_2 emissions resulting from its use. This asset may promote a net-zero emissions economy having hydrogen as a key energy vector.

Although it is a "decarbonized" energy vector, hydrogen production can incur into GHG emissions. These emissions are significant in a large part of the current global hydrogen supply, which is dominated by processes using fossil fuels as feedstock and that do not capture carbon dioxide.

For hydrogen to effectively achieve the goal of mitigating climate change, emissions from its production need to be minimized. Ensuring this reduction requires methodologically consistent quantification, generally based on life cycle assessment with properly established boundaries and parameters.

To illustrate the emissions involved in a hydrogen production process, the concept of carbon intensity (CI) is adopted, which is internationally recognized and used for the definition of policies and measures for GHG emissions mitigation. This concept is defined in Brazil by law within the scope of the National Biofuels Policy (RenovaBio) (BRASIL, 2017).

Concept: carbon intensity (CI)

According to Brazilian Law 13,576/2017, CI is the "ratio of greenhouse gas emissions, based on a life cycle assessment, calculated for the fuel production process, per unit of energy".

In RenovaBio, the quantification of emissions for each biofuel producer is performed using an *ad hoc* calculator named RenovaCalc. In this context, carbon intensity is expressed in grams of CO_2-equivalent[33] per megajoule of fuel (gCO_2eq/MJ). For hydrogen, this metric is also applicable, but it is more common for carbon intensity to be presented in kilograms of CO_2-equivalent per kilogram of hydroge ($kgCO_2eq/kgH_2$), that is, in emissions per unit mass of hydrogen.

Accordingly, the Brazilian National Low-Carbon Hydrogen Policy (established by Brazilian Law No. 14,948/2024) defines low-carbon hydrogen as "hydrogen with GHG emissions, according to life cycle analysis, with an initial value less than or equal to 7 $kgCO_2eq/kgH_2$" (BRASIL, 2024a).

In the global context, the International Energy Agency released, in April 2023, a report advocating that carbon intensity[34] should be primarily adopted standard parameter for hydrogen-related definitions. According to the Agency, the use of colors referencing production routes, as well as terms such as "sustainable," "low carbon," or "clean," obscure the many possible emission levels within the same classification. These qualitative terminologies have proven incapable of providing assurance to investors, and it is argued that governments, by agreeing to adopt carbon intensity in national regulations, would facilitate harmonization between markets and international regulations (IEA, 2023).

[33] In RenovaCalc, which methodology adopts global standards and factors, the emissions of different greenhouse gases are converted to CO_2-equivalent using the Global Warming Potential characterization factors for a 100-year horizon (GWP100) from the IPCC Fifth Assessment Report and are allocated on an energy basis among the coproducts.

[34] The IEA adopts the term "emissions intensity." In this document, following the RenovaBio definition, the same meaning as "carbon intensity" is considered, with both incorporating the emissions of all greenhouse gases through life cycle.

Such conclusions are aligned with a report from the International Renewable Energy Agency (IRENA) and the organization RMI, published in January 2023. The central message of these institutions is that the establishment of a global hydrogen market will depend on the development and broad acceptance of certification systems that provide concrete information about the hydrogen production chain. Certification is the mechanism that allows for the identification of production system characteristics that cannot be verified in the hydrogen itself, including carbon intensity. Certificates would be required for industries that aim to use a low-emission feedstock or energy source, which, in turn, would allow them to guarantee this attribute in the products marketed to their customers (IRENA & RMI, 2023).

To further explore the topics of carbon intensity and hydrogen certification related to bioenergy, this chapter is divided into three sections. Section 5.2 presents the main parameters related to the carbon intensity of biomass-based hydrogen, followed by Section 5.3, which provides CI estimates for selected pathways. Section 5.4 aims to advance the understanding of low-carbon hydrogen certifications and how they relate to the bioenergy industry, particularly to biomass-based production routes.

5.2. Hydrogen carbon intensity

Each hydrogen production pathway has its own specific features. In terms of carbon intensity, the main feedstocks and inputs are key determinants, but the production processes and their parameters also have a non-negligible impact.

For electrolytic hydrogen, the main element influencing carbon intensity is the source of the electricity used. Renewable electricity sources such as hydropower, wind, and solar typically have low emission factors during use, in contrast to fossil-based energy sources such as natural gas and coal. If the electrolyzer is connected to the power grid, it accesses a mix of energy sources, which may require additional mechanisms to track the origin of the electricity used.

When hydrogen is produced from natural gas reforming, emissions are mainly associated with the conversion of fossil-based carbon, but also with the upstream stages of natural gas production and transport. These stages affect carbon intensity, particularly due to fugitive methane emissions, which have a high Global Warming Potential[35]. In turn, the characteristics of the hydrogen production process are highly relevant, especially regarding the implementation of carbon capture and storage. The CO_2 capture rates is a key determining factor in the carbon intensity of fossil-based hydrogen with CCUS (EPE, 2022c).

Like other pathways, biohydrogen has its own specific parameters that are decisive for its carbon intensity.

5.2.1. Hydrogen from biomass

In the case of hydrogen produced from biomass, GHG emissions are concentrated in the agricultural phase, similarly to current biofuel production systems. In other words, the carbon intensity of biohydrogen fundamentally depends on the specificities of feedstock production.

[35] The Global Warming Potential (GWP) is used to estimate, compare, and aggregate the relative climate effects of different greenhouse gases (GHGs). It is a measure of the relative radiative effect of a given substance compared to another, typically CO_2, integrated over a selected time horizon (UNFCCC, 2004).

Agricultural phase

The use of fertilizers stands out as one of the main sources of GHG emissions in the agricultural phase. Emissions from these inputs, particularly nitrogen-based ones, present two main dimensions: (i) fertilizer production process, which involves the hydrogen production step that is mostly executed through natural gas steam reforming, as presented in Chapter 3; and (ii) fertilizer application, which leads to the emission of nitrous oxide (N_2O), a potent greenhouse gas (MENEGAT, LEDO, & TIRADO, 2022). Other agricultural inputs, such as soil conditioners (e.g. limestone), also consist of relevant emission sources.

Furthermore, agricultural phase also incorporates emissions from the use of fossil fuels for biomass production and transport. First, modern farming requires intensive agricultural machinery activity, from cultivation to harvesting. Second, the transportation of biomass to processing centers tends to be fuel-intensive, since in many cases biomass is a resource with relatively low energy density. Typically, the machinery and trucks used for transportation run on diesel, which results in significant emissions, even though commercial diesel in Brazil consists of a blend of fossil diesel and biodiesel in defined percentages established by the CNPE.

For processes that use residues as feedstock, RenovaCalc methodology considers that the biomass does not carry emissions related to cultivation[36]. Thus, residual biomass stands out as an attractive alternative from a carbon intensity standpoint. On the other hand, the biomass transportation phase can become quite relevant in GHG emissions for these cases, especially when it involves the collection of dispersed raw materials.

The use of agricultural land is considered one of the main environmental, social, and economic impacts of biomass production. In this sense, some restrictions on the development of biofuels as an energy alternative can be observed in the global scenario, many of which are based on the premise that energy crops replace native vegetation. In most cases, however, such a premise does not match reality as other land-use alternatives are often employed. Specifically, several modeling methodologies have been developed to quantify the GHG emissions associated with indirect land use change (iLUC), resulting in numerical emission values or approaches that penalize feedstocks considered to have high iLUC potential in programs[37] that account for biofuels and reward their performance in terms of GHG emissions. Whitin RenovaBio's framework, the regulatory approach regarding land-use change is risk-management–based, with eligibility criteria adopted to authorize biomass cultivation areas (ANP, 2018; MOREIRA, et al., 2024). In a recent report, the International Energy Agency indicates the qualitative risk management[38] solution as a good option, recognizing that emissions calculated by models are neither measurable nor verifiable, which creates divergences in GHG accounting and allows for arbitrariness in assigning values to feedstocks or production routes (IEA, 2024g).

[36] In RenovaBio, the concept is adopted that biomasses considered as residues are exempt from environmental burden, that is, "they are not assigned GHG emissions related to their generation, with only those occurring from their collection and transportation to the processing unit being accounted for" (MATSUURA, et al., 2018).

[37] The Low Carbon Fuel Standard (LCFS), regulated by the California Air Resources Board, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), from the International Civil Aviation Organization, are examples of programs that incorporate numerical GHG values from iLUC derived from models. The Renewable Energy Directive (RED) of the European Union and the Clean Fuel Regulations of Canada are examples of programs that use an approach penalizing feedstocks considered to have high iLUC potential (IEA, 2024g).

[38] The report was produced to support the Brazilian presidency of the G20 in 2024. Additionally, the Agency suggests evolving toward controlling the causes of these emissions through the universal application of land use regulations and support for better agricultural practices, emphasizing the importance of a policy portfolio covering different sustainability criteria with the goal of minimizing undesired impacts of biofuel production (IEA, 2024g).

Industrial phase

The biomass conversion phase carried out in industrial plants tends to be less significant in terms of GHG emissions according to Brazilian historical data on biofuel production systems (MATSUURA, et al., 2018).

For example, in the case of sugarcane ethanol production, the energy source for the plants is sugarcane bagasse, a lignocellulosic byproduct from sugarcane milling that is burned in boilers for combined generation of steam and electricity. Dedicated (full) corn ethanol plants, in turn, have adopted cogeneration using an additional input, wood chips.

In both cases, the processes are driven by renewable energy from biomass, avoiding potential use of fossil fuels and the high associated emissions. For comparison, it is worth considering U.S. corn ethanol, the world's largest producer of this biofuel. Typical plants in the United States use natural gas as the energy source, a practice that increases the carbon intensity of ethanol.

Although emissions from the industrial phase are not high among the main Brazilian biofuels, the characteristics and performance of the industry are not irrelevant in calculating carbon intensity. As the chain emissions are allocated among the products and their quantities, industrial yield has a decisive influence on the carbon intensity of biofuels, a concept also valid for hydrogen from biomass.

Biomass utilization

A more efficient process, that is, one that produces more H_2 from the same biomass, will have the emissions of the supply chain distributed over a greater quantity of product, reducing its carbon intensity.

5.3. Carbon intensity estimates for biohydrogen

In this section, the carbon intensity of hydrogen produced from the steam reforming of biomethane, and ethanol is evaluated as a means of providing a preliminary estimate. The calculations are carried out using the certifications currently in force under RenovaBio to estimate the carbon intensity of the feedstocks. For the hydrogen conversion step, only the process yield was considered, without including other potential associated emissions. Subsequently, the possibility of adopting carbon capture and storage technologies is presented as a potential solution to reduce or turn negative the carbon intensity of biohydrogen.

5.3.1. Production from biomethane

As presented in Chapter 2, biogas can be used for hydrogen production. One alternative is to use it directly in the dry reforming process (Equation 3), which utilizes the CH_4 and CO_2 components of the gas obtained from anaerobic digestion. With purification to biomethane, steam reforming (Equation 2) is the most well-established technological solution, due to the mature processes developed for natural gas.

Biomethane production qualifies as one of the biofuel routes eligible for certification under RenovaBio. That is, the production and commercialization of biomethane can directly generate Decarbonization Credits (CBIO).

Recap

Biomethane, a standardized biofuel rich in CH_4 derived from biogas purification, is interchangeable with fossil natural gas.

This characteristic becomes relevant in the context of hydrogen production, as steam methane reforming of natural gas is the dominant process for H_2 production worldwide.

For this exercise of estimating the carbon intensity of biohydrogen, the carbon intensity of national biomethane production is used as a basis, based on data from RenovaBio. In December 2024, there were three certified biomethane production plants, as shown in Table 5, with two based on urban waste deposited in landfills and one associated with the sugar-energy sector.

Table 5. ***Parameters of biomethane plants certified under RenovaBio.***

Parameter - biomethane	Unit	Value
Number of certified producers		3
Minimum CI	*[gCO₂eq/MJ]*	5,9
Maximum CI	*[gCO₂eq/MJ]*	11,0
Simple average CI	*[gCO₂eq/MJ]*	9,0
Capacity-weighted average CI	*[gCO₂eq/MJ]*	8,8

Source: EPE based on (ANP, 2024a; ANP, 2024b).

Considering that residues do not carry emissions related to production, the carbon intensities of the certified biomethane plants are relatively low, and the producing facilities are among those with the highest energy-environmental efficiency ratings in RenovaBio.

To estimate the carbon intensity of biohydrogen produced from biomethane, it is also necessary to consider the process yield. The overall transformation reaction is presented in 13[39]:

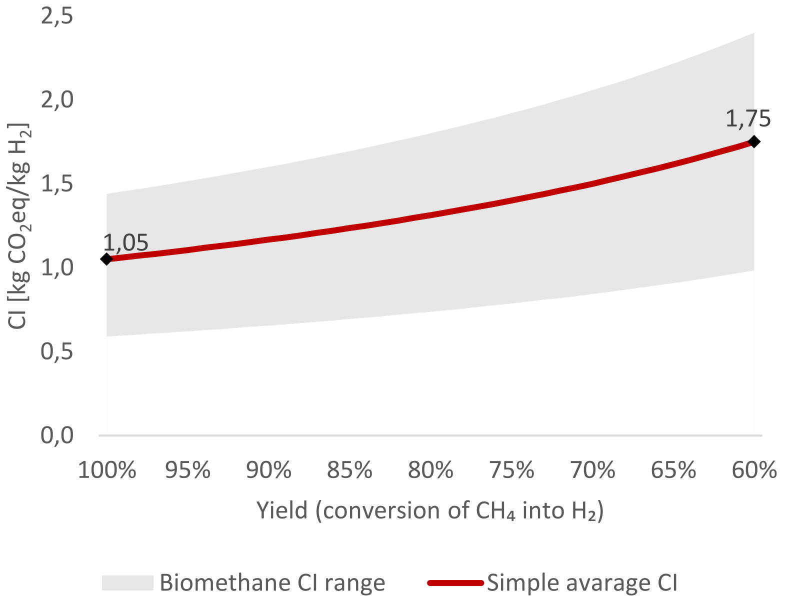
$$CH_4 + 2\,H_2O \rightarrow CO_2 + 4\,H_2 \qquad 13$$

Ideally, that is, with a 100% yield, 4 moles of H_2 would be produced for each mole of CH_4, or 0.5 kg of H_2 for each kg of CH_4. The actual yield, that is, the fraction of CH_4 effectively converted into H_2, can be significantly lower, at around 65%[40]. Based on these elements, *Chart 8* shows the carbon intensity of biohydrogen produced from biomethane reforming. It can be observed that the emissions calculated for this route comfortably meet the threshold of 7 $kgCO_2eq/kgH_2$ required by Brazilian legislation for low-carbon hydrogen.

[39] The overall equation combines steam reforming with the water-gas shift (WGS) reaction, presented in Chapter 2, adopted with the objective of maximizing H_2 production.

[40] The definition of yield adopted considers both the inefficiencies in the chemical conversion of the reactant into product and the consumption of the fuel itself to meet the process energy requirements.

Chart 8. Estimated carbon intensity of hydrogen produced from biomethane as a function of conversion yield and RenovaBio certifications.



Source: EPE based on (ANP, 2024a; ANP, 2024b).

It is worth mentioning that the calculation of the carbon intensity of biomethane, under certain methodologies, may consider emissions related to changes in waste management. This is because the adoption of anaerobic digestion for the purpose of producing biogas and biomethane alters the conditions of organic matter degradation and has the potential to avoid methane emissions that would naturally occur.

Due to the high Global Warming Potential (GWP) of methane, this aspect can have a significant influence on the carbon intensity of biogas and biomethane, even leading to substantially negative values. The Low Carbon Fuel Standard (LCFS) program in California, for example, certifies a series of biomethane production pathways with carbon intensity values on the order of - 200 e -300 gCO_2e/MJ (CARB, 2024), and this factor is recognized in studies evaluating the carbon intensity of hydrogen produced from biogas/biomethane (ANTONINI, et al., 2020; ZHOU, SWIDLER, SEARLE, & BALDINO, 2021).

On the other hand, studies indicate that the biogas and biomethane production chain can have fugitive methane emissions, which are difficult to measure (GASPER & SEARCHINGER, 2018; GRUBERT, 2020). Therefore, there is considerable uncertainty regarding the carbon intensity of biomethane and, consequently, of the hydrogen produced from this pathway.

5.3.2. Production from ethanol

Ethanol is the biofuel with the highest production level in Brazil. As a liquid fuel with an established distribution network throughout the country, studies have proposed using it as an energy carrier for decentralized hydrogen production.

For the exercise of estimating the carbon intensity of biohydrogen, data from RenovaBio are adopted. In December 2024, there were 286 ethanol production plants certified under RenovaBio, with carbon intensity values shown in Table 6. For plants with certification for both anhydrous and hydrated ethanol, the value for hydrated ethanol was adopted.

Table 6. *Parameters of ethanol plants certified under RenovaBio.*

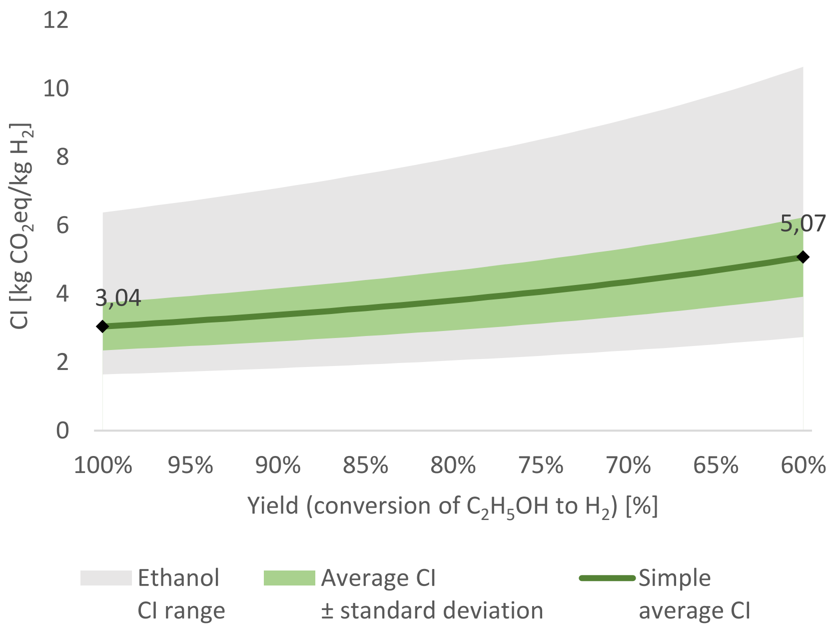
Parameter - ethanol	Unit	Value
Number of certified plants		286
Minimum CI	*[gCO_2eq/MJ]*	15,1
Maximum CI	*[gCO_2eq/MJ]*	58,7
Simple average CI	*[gCO_2eq/MJ]*	28,0
CI standard deviation	*[gCO_2eq/MJ]*	6,4

Source: EPE based on (ANP, 2024a; ANP, 2024b).

Hydrogen production from ethanol is governed by Equation 5, and the resulting carbon intensity also depends on the process yield.

Ideally, that is, with a 100% yield, 6 moles of H_2 would be produced for each mole of C_2H_5OH (ethanol), or 0.26 kilograms of H_2 for each kilogram of C_2H_5OH. The actual yield, that is, the fraction of C_2H_5OH effectively converted into H_2, can be significantly lower.[41]. Chart 9 shows the carbon intensity of biohydrogen produced from ethanol reforming. It can be observed that the emissions calculated for this route also comply with the 7 $kgCO_2eq/kgH_2$ threshold required by Brazilian legislation for low-carbon hydrogen, except in cases of plants at the upper limit of carbon intensity and with lower conversion yield.

Chart 9. Estimated carbon intensity of hydrogen produced from ethanol as a function of conversion yield and RenovaBio certifications.



Source: EPE based on (ANP, 2024a; ANP, 2024b).

The carbon intensity (CI) of biohydrogen produced from ethanol was also evaluated by WWF-Brasil (2023). The results indicated a CI of 2,27 $kgCO_2e/kgH_2$, which makes it competitive in terms of

[41] The definition of yield adopted considers both the inefficiencies in the chemical conversion of the reactant into product and the consumption of the fuel itself to meet the energy requirements of the process.

emissions with hydrogen produced by electrolysis from solar (3,28 $kgCO_2e/kgH_2$) and wind (1,76 $kgCO_2e/kgH_2$) sources, according to estimates published in the same report (WWF-BRASIL, 2023).

5.3.3. Biohydrogen production with carbon capture and storage

The term “carbon capture and storage” (CCS) refers to a set of activities that aim at permanently storing CO_2 into geological reservoirs, contributing to climate change mitigation. CCS can be applied to carbon streams resulting from the conversion of fossil fuels and biomass, as well as from other industrial processes and direct air capture.

In simplified terms, traditional bioenergy processes are ideally limited to GHG neutrality, as they return the carbon absorbed through photosynthesis to the atmosphere during conversion or combustion processes. By introducing CCS to bioenergy, a carbon flow from the atmosphere to a geological reservoir can be created, resulting in “negative emissions” (i.e., the removal of CO_2 from the atmosphere).

Considering the global challenge of eliminating all GHG emissions within a timeframe compatible with meeting climate agreements, it may be necessary to implement large-scale CO_2 removal solutions, reinforcing the role of bioenergy combined with CCS.

The conversion of biomass into hydrogen involves removing all the carbon from the biomass in typically steady conversion steps, as hydrogen consists of a carbon-free energetic vector. Thus, the production of pure hydrogen from biomass via thermochemical routes presupposes the removal of carbon during the gas purification stage, typically generating streams highly concentrated in CO_2 that can enable CCS operations.

In contrast to hydrogen, other biofuels are generally composed of carbon, hydrogen, and/or oxygen. This is the case of ethanol, biodiesel, and biogas, for example. These products, therefore, retain at least part of the carbon that originally constituted biomass feedstock. Moreover, the combustion of these biofuels in mobile units, such as vehicles, is not well suited for carbon capture.

Carbon removal from the atmosphere

Hydrogen is an energy carrier that allows for maximizing the carbon capture from biomass during energy conversion.

As a result, the carbon intensity of biohydrogen produced with CCS can reach highly negative values, which may attract interest even greater than that of the energy generated.

The possibility of generating “carbon-negative” hydrogen is a unique feature of biomass routes among the various low-carbon hydrogen production pathways. Puig-Samper et al. (2024) present a literature review comparing emission values calculated through life cycle analyses for ten hydrogen production routes, demonstrating that the biomass pathway was the only one capable of generating negative emissions (PUIG-SAMPER, BARGIACCHI, IRIBARREN, & DUFOUR, 2024).

In this regard, other authors also recognize the “carbon-negative” potential and highlight this feature as a central opportunity of biomass hydrogen. For example, a report from the Center on Global Energy Policy at Columbia University (USA) states that “the potential value of carbon removal achieved by biohydrogen, particularly carbon-negative hydrogen derived from biomass residues with CCS, far exceeds its energy value” (LOU, et al., 2023).

Another U.S. study, from Princeton University (LARSON, et al., 2020), points out that “from 2030 onward, biomass hydrogen with permanent CO_2 capture and storage becomes a cost-competitive technological option due to the high value of associated negative emissions.” The different scenarios evaluated for net-zero emissions by 2050 in the United States indicate growth for this pathway, contributing significantly to the total hydrogen supply and being the route adopted for a substantial portion of biomass among energy uses.

The quantitative assessment of the carbon intensity of biohydrogen with CCS varies across pathways and fundamentally depends on the emissions involved in the biomass production chain and the CO_2 capture rates of the process. Other relevant parameters exist but are specific to certain pathways, as presented, for example, for biomethane in the previous section.

In international literature, quantitative estimates of the carbon intensity of biomass hydrogen with CCS highlight the potential for negative emissions. Lou et al. (2023) evaluated biohydrogen produced from residues via the gasification route and report a carbon intensity ranging from -14,5 e -22,2 $kgCO_2eq$ per kg of H_2. In Parkinson et al. (2019), biohydrogen emissions were calculated ranging from -11,7 to -17,5 $kgCO_2eq$ per kg of H_2. Ina study from CCC (2018), the carbon intensity was estimated[42] to range from approximately -13,3 to -19,3 $kgCO_2eq$ per kg of H_2 (LOU, et al., 2023; PARKINSON, et al., 2019; CCC, 2018).

5.4. Biomass hydrogen and certification schemes

As presented in Section 5.1, there is a consensus that qualitative classifications, such as the use of colors, although widely used to designate hydrogen production pathways, are insufficient to support the development of the market and regulations for low-carbon hydrogen (IEA, 2023; IRENA & RMI, 2023).

In their place, it is proposed to disseminate objective criteria to be met and/or assessed to characterize hydrogen. The tasks of establishing the requirements and certifying the characteristics of hydrogen production systems are carried out by certification schemes, generally following standards established in regulations from different jurisdictions (DENA; WEC, 2022).

It should be noted that the International Energy Agency (IEA, 2023) advocates for the adoption of carbon intensity, which, based on an international understanding of the methodology, would provide a fundamental parameter for comparison among pathways and producers, as well as for interoperability among different regulations and certification schemes. This harmonization would not preclude the discretion of countries and regions to establish their own carbon intensity limits or to consider other sustainability criteria, such as energy source, land and water use, and even socioeconomic aspects.

Although the low-carbon hydrogen market is still incipient, there are several certification schemes for hydrogen and its derivatives. These schemes are adopted for recognizing compliance with voluntary frameworks, regulatory obligations, or criteria linked to the granting of incentives (IEA, 2023).

Currently, most certification schemes, reflecting the main existing hydrogen policies, have focused on the water electrolysis pathway using renewable energy sources. Thus, the main certification criteria are related to ensuring that the energy supply is low-emission, including measures to prevent "leakage" of emissions to the rest of the grid – such as linking to recently installed power generation plants and ensuring spatial and temporal correlations between generation and consumption.

[42] In CCC (2018), the values are presented in graphical form and in the unit gCO_2/kWh, having been converted considering the lower heating value of hydrogen to allow comparison.

On the other hand, the certification of hydrogen derived from biomass must incorporate aspects related to the agricultural production phase, which are inherently complex to monitor and audit, potentially resulting in greater challenges for its development.

6. Opportunities for the mutual development of hydrogen and bioenergy in Brazil

6.1. Relationships between hydrogen and bioenergy markets

Throughout this Technical Note, different ways in which bioenergy systems interact with the emerging low-carbon hydrogen market have been presented. The focus was on the contributions of bioenergy to the hydrogen supply (Chapter 2) and demand (Chapter 3), as well as on aspects that cover the interface between both dimensions, such as the production of synthetic fuels (Chapter 4) and the carbon intensity of biomass-derived hydrogen (Chapter 5).

This section (6.1) aims to highlight aspects that may typify a relationship of interdependence and mutual reinforcement between low-carbon hydrogen and bioenergy markets. For this purpose, it revisits the knowledge presented in previous chapters and incorporates new elements that support the development of these relationships.

The content presented here is briefly illustrated in *Figure 14*, which outlines the synergies between bioenergy and hydrogen, highlighting the benefits from the "perspective" of each market.

	OPPORTUNITIES GENERATED BY THE SUPPLY OF H_2 FROM BIOMASS	OPPORTUNITIES GENERATED BY THE USE OF BIOGENIC CO_2	OPPORTUNITIES GENERATED BY THE DEMAND FOR H_2 BY BIOENERGY
FOR BIOENERGY SYSTEMS	✓ Value-addition options for biomass ✓ Utilization of residues	✓ Biofuels with negative carbon emissions ✓ Coproduct valorization	✓ Reduction of product carbon intensity ✓ Competitiveness gains ✓ Production of new biofuels
FOR THE LOW-CARBON HYDROGEN CHAIN	✓ Diversified and distributed supply ✓ Geographic, temporal, and product-characteristics complementarity	✓ Complementary feedstock to low-carbon hydrogen use in chemical applications	✓ Consistent national demand across the territory

Figure 14. Opportunities created by relationships between bioenergy systems and low-carbon hydrogen market.

Source: EPE.

Icons obtained from flaticon.com

6.1.1. Mutual contribution of supply and demand

From the perspective of the bioenergy market, low-carbon hydrogen is a relevant input that, directly or through derivatives, can contribute to reducing the carbon intensity of its products and to creating new opportunities by enabling advanced biomass conversion processes.

Conversely, the demand from the bioenergy sector can support the development of low-carbon hydrogen market, as it increases supply and generates robust demand needed for scale-up.

Reciprocally, a broad and dynamic market for hydrogen and its derivatives can become a high-value option for bioenergy.

6.1.2. Low-carbon hydrogen supply complementarity

A particular case of synergy between hydrogen and bioenergy markets lies in the potential supply of hydrogen from biomass.

From this perspective, the complementarity of features between biomass pathways, which are already diverse, and other low-carbon hydrogen production routes stands out, especially comparing with water electrolysis and natural gas reforming with CCUS pathways.

Some of the complementary characteristics between these routes are geographic distribution, temporal availability, and the condition of hydrogen as a product, which can primarily direct it to specific uses. Below, a brief description of each of these aspects is proposed, summarized in Table 7.

Table 7. ***Summary of complementarities among major low-carbon hydrogen production pathways.***

Production and/or potential feature	Water electrolysis with renewable sources	Natural gas reforming with CCUS	Biomass (thermochemical routes)
Geographic distribution in Brazil (best potentials)	Northeast region.	Coastal region – Northeast and Southeast.	Central-West, Southeast, and South regions.
Temporal relationship	Uncontrolled production if connected directly to wind and solar. Requires grid connection or energy storage for firm supply.	Firm or flexible supply.	Seasonality of biomass production. Firm supply depends on biomass availability. Potential for flexible supply.
Condition of hydrogen as a product	Pure H_2, in suitable conditions for use in fuel cells, for example. Requires an external carbon source for synthetic fuel production.	Production of synthesis gas as an intermediate, with fossil carbon that must be permanently stored to constitute low-emission H_2.	Production of synthesis gas with biogenic carbon. Potential for low-emission synthetic fuel production. Requires purification to obtain high-concentration H_2.
Carbon intensity	Function of the electricity source used. Can reach near-zero values.	CCUS requires high capture rates to reach low carbon intensity levels.	Function of biomass production conditions, with low emissions in the case of residues. May be carbon-negative if combined with CCUS.

Source: EPE

Geographic distribution

In terms of geographic distribution, the greatest Brazilian wind potentials are in the Northeast region and in the state of Rio Grande do Sul. The Northeast region also holds the greatest solar potential of the country. Therefore, it concentrates the most competitive regions for electrolytic hydrogen production. Strategically, this potential also ensures closer proximity to markets with potential demand for hydrogen and derivatives, notably the European market.

In the case of natural gas hydrogen with CCUS, Brazilian gas supply is mainly located along the coast, from the Northeast to the Southeast regions, where pipeline infrastructure exists.

Finally, energy crops and waste generation for hydrogen generation are predominantly inland resources, for which the states of the Central-West, Southeast, and South regions currently stand out.

There is, therefore, high geographic complementarity in Brazil for the routes considered in Table 7.

Temporal availability

Hydrogen supply based on renewable electricity sources is, similarly to these sources, uncontrollable. Brazil has the possibility of connecting electrolyzers to the grid with a relatively low-carbon average supply, but projects directly linked to wind and/or solar generation or that limit production to periods with lower hourly prices and/or electricity carbon intensity on the grid may be characterized by lower utilization factors. In these cases, hydrogen costs may increase, and storage of either energy or hydrogen may be necessary to meet demand.

In turn, natural gas hydrogen production has the profile of large, concentrated plants located near the supply or gas infrastructure.

The hydrogen potential from biomass, however, encompasses different business models, ranging from seasonality tied to biomass harvesting to the ability to provide hydrogen in a firm or flexible manner, using products such as biogas and ethanol.

Hydrogen as a product

As addressed in Chapter 2 and Chapter 4, biomass conversion routes can be used to obtain pure hydrogen or to produce synthetic fuels.

The main routes originating from biomass, particularly the thermochemical ones, produce syngas, a mixture of H_2, CO, and other gases.

Syngas can undergo the water-gas shift reaction (WGS) to maximize hydrogen production, converting carbon into CO_2, making H_2 separation necessary for uses that require high purity.

Alternatively, syngas can be a precursor for synthetic fuels (hydrocarbons), using the Fischer-Tropsch reaction as the mechanism. This alternative is suitable for biomass precisely because of the presence of carbon in its composition and, consequently, in syngas. Biogenic carbon enables the production of low-emission synthetics.

Water electrolysis produces H_2 directly at high purity. Therefore, this route stands out as highly suitable for uses that require this asset. To produce synthetic fuels — in this case, electrofuels (e-fuels) — an external carbon source is necessary. Ideally, this carbon should originate from the atmosphere, either through direct air capture or biomass conversion, incurring additional costs.

6.1.3. Co-products recovery: CO_2 and O_2

The use of co-products is another source of synergy between bioenergy and hydrogen. Below, it is described how biogenic CO_2 and O_2 generated from water electrolysis can strengthen this relationship.

Capture and use of biomass CO_2 for reaction with hydrogen

A particular case of this synergy is based on the capture of carbon from biomass. Given that it consists of carbon removed from the atmosphere through photosynthesis, the CO_2 captured during biomass processing is a candidate for combination with hydrogen to produce hydrocarbons (synthetic fuels) with low carbon emissions.

One of the most evident opportunities for carbon capture from biomass is found in alcoholic fermentation, the core process in ethanol production. During fermentation, CO_2 is produced at high purity, facilitating its collection and reducing the costs of the capture step. This CO_2 can be directed to geological storage and potentially achieve negative emissions for ethanol production. The reaction with hydrogen, in turn, is a form of CO_2 utilization.

Another type of biomass processing that generates particularly relevant capture opportunities is anaerobic digestion. This process is associated with the treatment of organic waste and produces biogas, a gas mixture composed of CH_4 (methane) and CO_2. With biogas, thermal and/or electrical energy can be generated directly, but it is also possible to produce biomethane, a fuel with high CH_4 purity that resembles fossil natural gas. To obtain it, the biogas undergoes a purification or upgrading process, which is fundamentally a separation between CO_2 and CH_4. CO_2 is, therefore, a co-product of biomethane production made available in high concentrations.

As presented in Chapter 4, the direct reaction of biogas CO_2 with H_2 enhances CH_4 production and simultaneously purifies the biogas, since the impurity (CO_2) is consumed. This is an alternative to upgrading that directly proposes the combination of bioenergy and hydrogen projects, reinforcing the synergies between these markets indicated in this Technical Note.

Finally, the potential capture of CO_2 from biomass combustion operations is also noteworthy. The use of biomass such as sugarcane bagasse, black liquor, and wood chips for cogeneration of electricity and thermal energy in boilers is a common practice in several industrial segments. Due to the low CO_2 concentrations of post-combustion streams (3–15%) compared to those found in ethanol and biomethane plants, these operations tend to involve higher costs. Even so, the adoption of capture in thermal plants using biomass or fossil resources is expected to grow worldwide until 2030 (IEA, 2024f). In this context, the links between CCUS, bioenergy, and hydrogen chains can be further strengthened. CCUS is necessary to enable the supply of low-carbon hydrogen from natural gas. Any potential development of CCUS infrastructure could facilitate its adoption in bioenergy and increase the attractiveness of biohydrogen production.

Some of the advantages of using hydrogen produced from biomass are summarized in *Figure 15.*

Figure 15. Main advantages of biomass use for hydrogen production.
Source: EPE

Use of O_2 (co-product of electrolysis) in the bioenergy industry

Hydrogen production via electrolysis using renewable electricity sources simultaneously produces oxygen (O_2) at high purity. With the perspective of scale-up and feasibility of this technological route, a new oxygen supply in search of demand can be anticipated. It is noted that the production of 1 kg of hydrogen results in the production of 8 kg of oxygen

Co-product valorization

If viable, the commercialization of oxygen can contribute to the viability of electrolysis and to the acceleration of the hydrogen market.

This promising oxygen supply has led to studies mapping potential applications of the gas. One such study was conducted by Energiforsk, the Swedish Energy Research Center, an organization linked to the country's industry. The authors highlighted that the forecasted oxygen production associated with electrolyzers is expected to exceed more than four times the amount produced in the country in 2020 by 2030, when 5 GW of installed capacity for hydrogen production is anticipated (ENERGIFORSK, 2023). Two of the potential applications mentioned in the report are:

a) Oxygen as a reagent in industry, including for the gasification process;
b) Oxygen-enriched combustion.

Both these applications can be useful in the bioenergy industry.

The gasification process, addressed in a), is one of the main processes for converting biomass into energy and was described in Chapter 2 of this Technical Note as one of the hydrogen production routes. When used as an oxidizing agent, pure oxygen allows the production of syngas compositions richer in hydrogen and carbon monoxide compared to the product obtained when atmospheric air is employed. The result occurs mainly due to avoiding contamination with air nitrogen. Therefore, using oxygen brings benefits to gasification and enables its adoption for applications requiring syngas under more concentrated conditions. It should be noted, however, that gasification can also be promoted with water vapor, with the potential to maximize H_2 production by combining the hydrogen content of biomass with that of water (H_2O).

Oxygen-Enriched Combustion, indicated in b), is also a way to complement or replace atmospheric air. This process can be adopted in equipment such as boilers and combustion engines. As a result, combustion occurs at higher temperatures, which may require selected equipment and materials. Oxygen enrichment affects NO_X production, increasing it due to higher temperatures and decreasing it due to the lower proportion of nitrogen from the air, with the prevailing trend being a net reduction in NO_X.

The use of pure oxygen for combustion is commonly named oxy-combustion. Oxy-combustion is indicated as an alternative to enable CO_2 capture in fuel use, as it ensures that the exhaust gases are richer in CO_2. With a potential abundance of O_2 supply near biomass conversion units from electrolytic hydrogen production, it may become feasible to carry out oxy-combustion and capture CO_2 from biomass combustion.

As presented in Chapters 3 and 4, captured CO_2 can be combined with electrolytic hydrogen to produce synthetic fuels. Alternatively, CO_2 can be directed to geological storage, improving the carbon intensity of biomass products.

An additional application of O_2 is found in wastewater treatment systems, particularly in the aeration stage. When performed, this process generally uses atmospheric air, resulting in high energy consumption. The use of O_2 would reduce the volume handled and the associated energy demand. One proposed arrangement places water electrolysis at treatment plants as a supplier of O_2 for aeration and as a source of hydrogen to promote methanation of CO_2 from biogas, which can also be produced in the anaerobic digestion of organic effluents and sludge. Additionally, it is suggested to use the heat from the exothermic methanation reaction for the process (ENERGIFORSK, 2023; MURPHY, RUSMANIS, GRAY, & O'SHEA, 2024).

6.2. Business models for hydrogen production and use linked to bioenergy in Brazil

As presented throughout this document, there is a range of alternatives for utilizing biomass as a source of hydrogen and its derivatives, as well as for the use of hydrogen in the bioenergy industry.

This section aims to present development perspectives for these solutions and models of how projects can be implemented in practice, taking advantage of bioenergy potential. It consists of a non-exhaustive list based on projects under development in Brazil, which are recalled under their respective arrangements.

In this way, the goal of this section is to highlight some of the numerous solutions involving bioenergy and hydrogen that could become viable in the context of the energy transition.

Residual biomass as feedstock for syngas and synthetic fuels

As presented in Chapter 4, hydrogen produced from biomass is commonly generated within syngas, that is, with a carbon source, under conditions favorable to hydrocarbon production. Therefore, instead of "stopping" at hydrogen, it serves as an intermediate product for molecules with broader demand, established infrastructures, and greater ease of distribution to consumption.

The opportunity to produce renewable fuels for hard-to-abate sectors, such as aviation, is the focus of at least three national projects, all following routes with intermediate syngas production. In particular, these projects use residues as feedstocks and, in doing so, can generate fuels with low carbon intensity and low risk of land-use change, meeting the main requirements to access markets with higher remuneration for environmental attributes.

In Paraná State, a plant that converts residues from the sugar-energy sector into biogas received financing to invest 15 million reais in the installation of a pilot plant for aviation bio-kerosene via Fischer-Tropsch synthesis. The project is developed in partnership with the University and has support from Finep (MACHADO N. , 2023). The proposed route can be justified based on the unique scale of biogas in Brazil and the economic competitiveness of biogas in energy terms compared to other fuels.

Also in Paraná State, a pilot plant was inaugurated in 2024 using biogas and green hydrogen to produce a hydrocarbon mixture for sustainable aviation fuel (SAF) production. The unit consumes up to 50 Nm^3/day of biogas as a carbon source, combined with 53 Nm^3/day of electrolytic hydrogen to produce 6 kg/day of bio-syncrude. The project is led by national research institutions, in partnership with German cooperation and funding initiatives (CIBIOGÁS, 2024).

In 2023, a pilot plant to produce renewable hydrocarbons from a variety of feedstocks, whether gaseous, liquid, or solid, was inaugurated at a research institute in Rio Grande do Norte. One of the projects carried out at this unit involves converting glycerin into aviation fuel, with an investment of approximately R$ 4 million. Glycerin is a byproduct of biodiesel production through the transesterification of vegetable and animal oils. The process chosen for syngas production is the chemical looping, which avoids contact between the feedstock and atmospheric nitrogen by using a Solid Oxygen Carrier (SOC) (PROQR, 2019) (SENAI, 2023).

Use of biogenic CO_2 in chemical syntheses with low-carbon hydrogen

As presented in Chapters 3 and 4 and in Section 6.1, biogenic CO_2 can be used as a renewable carbon source for the synthesis of higher-value liquid or gaseous products, such as synthetic hydrocarbons or methanol. A particularly environmentally synergistic configuration for carrying out these processes is the use of electrolytic hydrogen, resulting in electrofuels or e-methanol.

The use of biogenic CO_2 from fermentation in sugarcane ethanol plants is an alternative that can expand the scope of activities and the product portfolio of existing biorefineries. In a recent assessment, it was shown that methanol production is competitive in various process configurations, with hydrogen cost being a central variable in the route’s economics. It is noted that while greater viability exists when fossil-derived hydrogen is used, achieving it with electrolytic hydrogen is challenging. On the other hand, the electrolytic route yields significantly more favorable environmental results (RESTREPO-VALENCIA, CAPAZ, & ORTIZ, 2025). From a systemic cost perspective, valorizing CO_2 within the plant itself is advantageous as it avoids transporting the carbon to another conversion site, but it creates challenges associated with establishing distributed hydrogen demand centers, which would require local hydrogen production or its transport to the plant.

The conversion of CO_2 into higher-value products is the focus of at least three national initiatives of medium or large scale in early stages of design, described below.

A memorandum of understanding (MoU) between private sector companies was recently signed to develop solutions to produce synthetic fuels and e-methanol from electrolytic hydrogen and biogenic CO_2 derived from black liquor combustion in the pulp and paper sector (SUZANO, 2024).

The Government of Pernambuco announced an agreement with the private sector for the establishment of an e-methanol production industry, with an investment of approximately R$ 2 billion. The project focuses primarily on the use of electrolytic hydrogen in combination with biogenic CO_2 from ethanol plants or landfills and aims mainly to serve the maritime fuels market (MACHADO N. , 2024; ROSA, 2024).

Finally, a research project carried out by a consortium between a university and private sector institutions and companies focuses on the development of two pilot plants to produce green hydrocarbons. The potential use of CO_2 from different sources is mentioned, but the consortium specifically highlights the consumption of gas from offshore operations (REPSOL SINOPEC BRASIL, 2021). Thus, this initiative does not have a specific focus on the use of biogenic CO_2. However, the development of CO_2 conversion technology into hydrocarbons in Brazil enables global advancement of the national industry, also facilitating the implementation of future business models associated with biomass utilization.

Biomethane and the use of existing infrastructure

As addressed in Chapter 3, the main global route for hydrogen production is natural gas steam reforming, while one of the primary demands lies in the production of nitrogen fertilizers. As is common in hydrogen applications, production is typically contiguous to utilization, meaning that gas reforming directly feeds the Haber-Bosch reaction and ammonia production in large-scale industrial complexes, usually strategically located near abundant and competitive natural gas supplies.

The use of these facilities to reduce emissions can constitute a competitive energy transition solution. In this context, biomethane emerges as a mature alternative, allowing full utilization of the industrial unit and the energy supply itself.

The establishment of supply contracts, as well as the use of biomethane tracking mechanisms[43], creates conditions for consumers to access the renewable features of biomethane without the requirement of physical molecule delivery. This allows access to a regionally and feedstock-diverse supply of biomethane, ensuring the production of low-carbon hydrogen without significant investment.

Under this model, a fertilizer plant in São Paulo announced the acquisition of 20,000 m³ per day of biomethane delivered through the gas network, representing 3% of the volume consumed by the industrial unit. The five-year contract was signed with a company in the sugar-energy sector, whose biomethane plant received operational authorization in 2024 (YARA, 2021) (RAÍZEN, 2021) (RAÍZEN, sd) (ANP, 2024a). In the same year, an agreement was announced with an industry for the commercialization of renewable ammonia produced from biomethane, with an expected acquisition of 600,000 tons in the first year (AJINOMOTO, 2024) (WEISS, 2024).

In another example of this model, Petrobras launched, in January 2025, its first call for proposals for the acquisition of biomethane and biofuel guarantee of origin certificates, in anticipation of the obligations established under the Fuel of the Future program. The initiative foresees the receipt of offers for firm contracts with deliveries starting in 2026 and long-term contracts, with biofuel delivery at different points, including the company’s refineries (PETROBRAS, 2025). In these cases, the renewable share in a refinery’s gas supply can indirectly represent the decarbonization of hydrogen generation used in refining.

Ethanol as a hydrogen carrier

The logistics of hydrogen storage and distribution are challenging across several dimensions, such as the lack of established infrastructure (DE BLASIO, PFLUGMANN, & LEE, 2021); low volumetric energy density; the requirement for conditioning at high pressures and/or very low temperatures, with significant energy penalties and evaporation losses (boil-off); substantial costs for storage and

[43] This is the case of the Biomethane Guarantee of Origin Certificate (CGOB), an innovation introduced by Brazilian Law 14,993/2024 (Fuel of the Future Law).

distribution (GHAFRI, et al., 2022; LIEBREICH M. , 2022; ZHANG, et al., 2023; SHAFIEE & SCHRAG, 2024); a molecule prone to leaks, with implications for the loss of a high-value product, safety risks, and climate impacts (FAN, et al., 2022; UK GOVERNMENT, 2022; OCKO & HAMBURG, 2022); among others.

Thus, although at first glance the "carbon-free" asset of hydrogen molecule seems promising for structural GHG emission reductions, the proposal to develop an energy system widely based on hydrogen as a carrier proves impracticalities to effective implementation.

Hydrogen's logistical challenges are the main drivers of several studies investigating a series of molecules that could act as hydrogen carriers, such as ammonia, methanol, and organic liquids (LOHC) (NIERMANN, BECKENDORFF, KALTSCHMITT, & BONHOFF, 2019; PEECOCK, HULL-BAILEY, HASTINGS, MARTINEZ-FELIPE, & WILCOX, 2024). These molecules could facilitate hydrogen logistics, being used directly or reconverted, though the intermediate steps entail additional costs and energy inefficiencies, as well as their own logistical challenges, including toxicity and safety considerations.

For these reasons, there is an opportunity for molecules that can be produced with low carbon emissions and have a high hydrogen content in their composition, particularly those that can be more easily converted to H_2 for end-use applications. Ethanol, with a chemical composition of six hydrogen (H) atoms for every two carbon (C) atoms, meets these requirements. In ethanol steam reforming, the same process responsible for converting methane[44] into H_2, the two hydrogen atoms present in water are also combined to generate additional H_2.

The H_2 logistics challenge

Ethanol as an energy carrier offers a solution to overcome the technical and economic challenges of developing hydrogen infrastructure.

Thus, the relative advantages of the biofuel can be leveraged as a liquid with high energy density at ambient temperature and low toxicity, enabling storage and transport without significant constraints. Within the national territory, the extensive existing distribution of biofuel constitutes an established infrastructural advantage of ethanol as a hydrogen carrier.

The crucial step in the development of this alternative is ethanol steam reforming, which must be mastered at competitive costs and in a safe manner. Technological mastery at different scales and/or in modular units would allow meeting various types of consumption, while operation on demand could provide a way to minimize hydrogen storage while addressing potential variable demands, representing a distinctive advantage of this route among low-carbon options.

Hydrogen and the ethanol market in Brazil

The proposal of ethanol as a hydrogen carrier has the potential to **expand the market for Brazil's main biofuel**, which is currently limited, in scale, to spark ignited cycle engines used in light vehicles, particularly flex-fuel models.

It should be noted that, with the ongoing energy transition, ethanol is also envisioned as a feedstock for SAF production via the AtJ route, as well as for direct use in maritime vessels and other heavy-duty vehicles.

A pilot project under development at a university is studying ethanol reforming at a refueling station for buses and light vehicles powered by hydrogen and equipped with fuel cells (USP, 2023). The replicability of this project's strict model assumes the commercial viability and widespread

[44] Methane has an H:C ratio of 4:1, the highest among hydrocarbons.

adoption of both hydrogen at refueling stations and the hydrogen-powered vehicles themselves, which does not depend solely on the ethanol production route. In the case of mobility, energy losses during conversion and the practicality of ethanol compared to hydrogen can be questioned, favoring the direct use of ethanol as a fuel. On the other hand, the choice of hydrogen could be justified by the higher energy efficiency of fuel cell technology compared to combustion engines.

A technological alternative is the *in-situ* production of hydrogen from ethanol directly within vehicles, which is still being studied at a non-commercial maturity level. Several vehicle manufacturers have recently announced research projects to develop these technologies in partnership with Brazilian universities and other science and technology institutions. The routes may involve the use of reformers integrated into the vehicle powertrain or fuel cells directly powered by ethanol (ZAPAROLLI, 2023).

Beyond mobility applications, demonstrating the viability of decentralized hydrogen production from ethanol could have implications for the supply of hydrogen to various industrial and other demand sectors.

Meeting the demands of (bio)refineries

As the energy transition progresses, the demand for drop-in hydrocarbons such as SAF and renewable diesel increases. In Chapters 3 and 4, hydrogen is presented as a key element in the main routes for producing these products, either as a fundamental component in fuel synthesis alongside a carbon source—both of which can come from biomass (via FT)—or as a reagent to facilitate the upgrading of complex renewable molecules (in the HEFA and AtJ routes).

Recap

The use of self-produced or purchased biomethane, whether directly or via certificates, is a strategy for decarbonizing H_2 from both biorefineries and oil refineries, as illustrated by a public call promoted by Petrobras and supported by the Future Fuel program.

Therefore, particularly in the second case, which refers to biorefineries, a demand for H_2 is created whose supply is not pre-established, meaning the production route is open to different options. Similarly, replacing hydrogen production in refineries can be a relevant measure in decarbonizing the oil and derivatives value chain.

Specifically, biorefineries can be integrated with biomass processing, which, in addition to producing target products, can generate organic residues and/or biomass-derived fractions that can serve as feedstocks for hydrogen production, meeting the process's own demands.

As an example, a potential arrangement could involve processing vegetable or animal oils in a biorefinery producing biodiesel and using the HEFA route for advanced biofuels. Glycerin, a byproduct of biodiesel, could supply H_2 for the hydrogenation step. Additionally, a sugarcane mill could be considered, whose vinasse and filter cake residues have been used as feedstocks in several biogas and biomethane production projects. As a next step, hydrogen could be generated from reforming processes to meet potential demand in converting ethanol into SAF via the AtJ route.

A project in France plans to convert a refinery into a biorefinery following a similar model, aiming to make it a "zero-oil platform" by 2025. The plan includes operating it with 75% residues as feedstock and maximizing SAF production, with biogas from the biorefinery supplying hydrogen to a reforming unit with a capacity of over 20,000 tons/year (TOTAL, sd) (TOTAL, 2020). In these models, biomass-derived hydrogen emerges as an option for valorizing residues, integrating activities, and ensuring the energy self-sufficiency of biorefineries.

7. Final considerations

The development and resilience of energy transition in Brazil require emission-reduction solutions that coexist with the promotion of the country's economy competitiveness. Leadership in the production of sustainable fuels and in the decarbonization of key sectors such as industry, if based on cost-effective principles, has the potential to drive a new cycle of investment attraction for national productive development, enabling the achievement of global market positions.

Hydrogen stands out in this context but faces challenges in creating new value chains and in infrastructure investments. Identifying bioenergy as a partner in these developments may represent a strategic differentiator for Brazil in leading the hydrogen industry and realizing its potential, leveraging biorefineries as drivers of plurality and competitiveness in supply and as anchors of demand.

The multiple hydrogen production routes from biomass, particularly the conversion of resources that Brazil consistently produces in abundance, can offer hydrogen with unique attributes. Notable advantages include negative emissions (when combined with CCUS) or the use of carbon contained in biomass for the production of synthetic hydrocarbons; decentralized H_2 production with relatively low logistical costs (via ethanol) and the utilization of existing infrastructure (via biomethane); and adding value to byproducts or organic residues (biogas/biomethane, glycerin, and lignocellulosic materials). From an investment perspective, the carbon abatement cost (measured in R$/kg CO_2) of hydrogen from biomass (specifically that produced through gasification routes) has been estimated to be lower than that of electrolytic hydrogen, particularly when associated with carbon use or capture, which highlights the potential of biomass routes as cost-effective options for decarbonization (IEA BIOENERGY, 2025).

In this regard, showcasing the potential of biomass aligns with the Brazilian strategy for hydrogen, whose guiding principles include recognizing the diversity of national resources and avoiding technological pre-selection.

Regarding demand, bioenergy systems present elements related to the main current applications of hydrogen, notably petroleum refining and the production of methanol and ammonia. The growing participation of bioeconomy activities could transform part of traditional refining into biorefining operations, with similar or additional hydrogen demands; expand the use of methanol for biodiesel production and create a new market for the product as a fuel; and enable the production of renewable-based ammonia, which would remain a critical input for nitrogen fertilizer production essential to agricultural productivity and biomass supply. It is noteworthy that, in this scenario, renewable hydrocarbons would be obtained from biorefining, along with products such as methanol and fertilizers that have minimal impact on the carbon intensity of bioenergy.

Therefore, a widespread, diversified, and competitive low-carbon hydrogen value chain tends to drive the evolution of bioenergy toward products sought after for decarbonization, such as sustainable aviation fuel and renewable diesel, and ensure compliance with increasingly stringent emission standards, as required by emerging international frameworks.

The convergence between bioenergy and hydrogen reinforces Brazil's potential to promote sustainable solutions for the energy transition, particularly those aligned with its national competitive advantages.

There are corelated sectors that can also contribute to and benefit from the development of hydrogen combined with bioenergy. The CCUS value chain, for instance, would play an instrumental role in enhancing several hydrogen production routes, including those from biomass, potentially maximizing the negative emissions of bioenergy. This same chain can also provide biogenic CO_2, one of the strategic elements for the utilization of electrolytic hydrogen, representing a clear synergy between biofuels and electrofuels.

On the other hand, it is important to acknowledge the challenges to realizing the mentioned opportunities, which are linked to broad ambitions for reindustrializing the country in highly competitive sectors that do not necessarily prioritize or capture value from environmental attributes. Addressing these challenges requires comprehensive measures that promote decarbonization, such as carbon pricing, represented by the creation of the Brazilian Greenhouse Gas Emissions Trading System (Brazilian Law No. 15,042 of December 11, 2024), as well as specific policies for hydrogen, bioenergy, and the activities that can catalyze this combination. It is also necessary to emphasize the importance of fostering industrial innovation to scale up and make economically competitive production processes associated with these value chains.

For hydrogen, it is worth mentioning the already approved Brazilian National Policy for Low-Carbon Hydrogen (Brazilian Law No. 14,948 of August 2, 2024) and the mechanisms being implemented under this framework—for example, the public call for the selection of hydrogen hubs conducted by the Ministry of Mines and Energy. This initiative has the potential to leverage the hydrogen industry in strategic sectors, driven by investor interest, through a model that recognizes production and consumption as adjacent activities, at least as an initial step until connection infrastructures become more economically rational.

In bioenergy, the Future Fuel Law (Brazilian Law No. 14,993 of October 8, 2024) expands the scope of biofuels to new routes and products directly involving hydrogen, highlighting the relationship between the two. RenovaBio, in turn, establishes a foundation by including the use of low-carbon hydrogen and its derivatives in the biofuel production chain within the life-cycle assessment, adding value to products through reduced carbon intensity and the generation of decarbonization credits.

Finally, from a cross-sectoral perspective, it is worth highlighting the New Industry Brazil (NIB) initiative, established through CNDI/MDIC Brazilian Resolution No. 1 of July 6, 2023, by the National Industrial Development Council. The NIB defines the guidelines of Brazil's industrial policy and sets out national development priorities through strategic missions. In this regard, the policy explicitly demonstrates Brazil's interest in value chains such as bioenergy and hydrogen directly through Missions I and V [45] and indirectly through Missions III and IV [46], establishing a favorable regulatory and political environment for strengthening and expanding these sectors.

The implicit presence of this relationship in current policies inspires its explicit recognition across multiple dimensions, which is the focus of this Technical Note. The alignment of the hydrogen and bioenergy sectors with a just and inclusive energy transition, reinforced by their mutual strengthening, indicates that national decarbonization strategies can be effectively applied to their development.

[45] Mission I of the NIB refers to "sustainable and digital agro-industrial value chains for food, nutritional, and energy security." Mission V refers to "bioeconomy, decarbonization, and energy transition and security to ensure resources for future generations".

[46] Mission III of the NIB refers to "sustainable infrastructure, sanitation, housing, and mobility for productive integration and urban well-being." Mission IV refers to "digital transformation of industry to increase productivity".

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