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COMPARATIVE LIFE CYCLE ASSESSMENT OF HYDROGEN PRODUCTION METHODS: EUCALYPTUS BIOMASS GASIFICATION VS NATURAL GAS STEAM REFORMING IN BRAZILIAN CONDITIONS

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AVALIAÇÃO COMPARATIVA DO CICLO DE VIDA DOS MÉTODOS DE PRODUÇÃO DE HIDROGÊNIO: GASEIFICAÇÃO DE BIOMASSA DE EUCALIPTO VS REFORMA A VAPOR DE GÁS NATURAL NAS CONDIÇÕES BRASILEIRAS

Dissertation presented to the Federal University of Lavras as part of the requirements of the Graduate Program in Environmental Engineering, with a concentration in Environmental Sanitation, for the attainment of the title of Master.

Approved on February 17, 2025.

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LAVRAS – MG

2025

DEDICATION

To my Creator, God.

To my parents, Alberto Vilanculos Ouana and Ermelinda Argentina Muchanga.

To my wife, Sara Da Graça.

And to my beloved daughter, Yana.

ACKNOWLEDGMENTS

First and foremost, I thank God, creator of the Heavens and the Earth, for His grace and blessings that sustained me throughout this journey.

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To everyone who, directly or indirectly, contributed to the completion of this work, my most sincere thanks.

“A vida é uma esteira onde caminhamos passo a passo, sem saber exatamente o que nos espera no final."

Paulina Chiziane

IMPACT INDICATORS

The study comparatively evaluated hydrogen production through eucalyptus biomass gasification and natural gas steam reforming in the Brazilian context, using Life Cycle Assessment (LCA) as an analytical tool. Social impacts are observed in the potential job creation along the renewable hydrogen production chain, especially in rural areas where eucalyptus production is expanding as a source of sustainable biomass. From a technological perspective, the research contributes to advancing knowledge on thermochemical and catalytic processes for biomass conversion into hydrogen, enabling a reduction in dependence on fossil fuels and fostering the development of new solutions for the energy sector. Economically, the results indicate that eucalyptus gasification presents technical feasibility and could become a competitive alternative to fossil-based hydrogen, aligning with decarbonization policies and the energy transition. The life cycle analysis highlights a significant reduction in greenhouse gas emissions for renewable hydrogen production, contributing to Brazil's climate goals and mitigating environmental impacts in the energy sector. Additionally, the study aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), promoting a more sustainable energy transition and strengthening environmental policies. Potential impacts include the expansion of renewable hydrogen use in industrial and transportation sectors, contributing to the diversification of the national energy matrix and enhancing energy security. The study also reinforces the importance of academic research in shaping public policies aimed at decarbonization and transitioning toward a low-carbon economy in Brazil.

INDICADORES DE IMPACTOS

O estudo avaliou comparativamente a produção de hidrogênio pela gaseificação da biomassa de eucalipto e pela reforma a vapor do gás natural no contexto brasileiro, utilizando a Avaliação do Ciclo de Vida (ACV) como ferramenta de análise. Os impactos sociais são observados no potencial geração de empregos ao longo da cadeia produtiva do hidrogênio renovável, especialmente em áreas rurais onde a produção de eucalipto se expande como fonte de biomassa sustentável. No aspecto tecnológico, a pesquisa contribui para o avanço do conhecimento sobre processos termoquímicos e catalíticos para a conversão de biomassa em hidrogênio, possibilitando a redução da dependência de combustíveis fósseis e fomentando o desenvolvimento de novas soluções para o setor energético. Do ponto de vista econômico, os resultados indicam que a gaseificação do eucalipto apresenta viabilidade técnica e pode se tornar uma alternativa competitiva ao hidrogênio fóssil, alinhando-se às políticas de descarbonização e transição energética. A análise do ciclo de vida evidencia uma significativa redução das emissões de gases de efeito estufa para a produção de hidrogênio renovável, contribuindo para o cumprimento das metas climáticas do Brasil e para a mitigação dos impactos ambientais do setor energético. Além disso, o trabalho está alinhado aos Objetivos de Desenvolvimento Sustentável (ODS) da ONU, especialmente aos ODS 7 (Energia Limpa e Acessível), ODS 9 (Indústria, Inovação e Infraestrutura) e ODS 13 (Ação contra a Mudança Global do Clima), promovendo uma transição energética mais sustentável e fortalecendo políticas ambientais. Os impactos potenciais incluem a ampliação do uso de hidrogênio renovável em setores industriais e de transporte, contribuindo para a diversificação da matriz energética nacional e para a segurança energética. O estudo reforça, ainda, a importância da pesquisa acadêmica na formulação de políticas públicas voltadas para a descarbonização e transição para uma economia de baixo carbono no Brasil.

ABSTRACT

Hydrogen is increasingly recognized as a promising alternative to conventional fuels, offering significant potential to drive the energy transition and reduce carbon emissions. However, the majority of hydrogen (H_2) production still depends on fossil fuel sources, highlighting the urgent need to explore more sustainable alternatives. Among these, hydrogen production through the gasification of biomass, particularly eucalyptus, has garnered considerable attention. To evaluate the environmental impacts of this approach, a life cycle assessment (LCA) was conducted, comparing it to the most common method, steam methane reforming (SMR) of natural gas, under Brazilian conditions. The study assessed three distinct scenarios to provide a comprehensive analysis of their environmental performance. i) SMR of natural gas, ii) SMR-CCS - SMR integrated with carbon capture and storage (CCS), and iii) Gasification-WGS - eucalyptus gasification coupled with the water-gas shift reaction. Using ReCiPe's midpoint (H) method, nine key impact categories were analyzed, with global warming (GW) identified as the most critical. Results revealed that SMR and SMR-CCS produce 17.5 kg and 10.5 kg of CO_2 equivalent emissions, respectively, while the Gasification-WGS scenario emits only 1.84 kg of CO_2 equivalent, reducing emissions by approximately 89% compared to SMR. Despite its lower GW impact, the SMR-CCS scenario showed higher impacts in other categories, whereas the Gasification-WGS scenario had increased eutrophication due to nutrient runoff from eucalyptus cultivation. These findings underscore the importance of assessing hydrogen production pathways comprehensively to ensure their sustainability and environmental viability. Biomass gasification, supported by photosynthesis and CCS technologies, demonstrates significant potential as a clean energy vector in the decarbonization scenario.

Keywords: Biomass gasification. Carbon emissions reduction. Sustainable energy. Energy transition, CO_2 capture and storage.

RESUMO

O hidrogênio está cada vez mais reconhecido como uma alternativa promissora aos combustíveis convencionais, oferecendo um potencial significativo para impulsionar a transição energética e reduzir as emissões de carbono. No entanto, a maior parte da produção de hidrogênio (H_2) ainda depende de fontes fósseis, destacando a necessidade urgente de explorar alternativas mais sustentáveis. Entre essas, a produção de hidrogênio por meio da gaseificação de biomassa, particularmente do eucalipto, tem ganhado atenção considerável. Para avaliar os impactos ambientais dessa abordagem, foi realizada uma avaliação do ciclo de vida (ACV), comparando-a ao método mais comum, a reforma a vapor de metano (SMR) do gás natural, em condições brasileiras. O estudo analisou três cenários distintos para fornecer uma análise abrangente do desempenho ambiental dessas tecnologias. i) SMR de gás natural, ii) SMR-CCS - SMR integrado com captura e armazenamento de carbono (CCS) e iii) Gaseificação-WGS - gaseificação de eucalipto acoplada à reação de deslocamento de água-gás. Usando o método de ReCipe Midpoint (H), foram selecionadas nove categorias de impacto, com o aquecimento global (GW) identificado como o mais crítico. Os resultados revelaram que SMR e SMR-CCS produzem 10,1 kg e 6,53 kg de emissões de CO_2 equivalente, respectivamente, enquanto o cenário de gaseificação-WGS emite apenas 1,23 kg de CO_2 equivalente, reduzindo as emissões em aproximadamente 89% em comparação com SMR. Apesar de seu menor impacto de GW, o cenário SMR-CCS mostrou maiores impactos em outras categorias, enquanto o cenário de gaseificação-WGS teve aumento da eutrofização devido ao escoamento de nutrientes do cultivo de eucalipto. Essas descobertas ressaltam a importância de avaliar as vias de produção de hidrogênio de forma abrangente para garantir sua sustentabilidade e viabilidade ambiental. A gaseificação de biomassa, apoiada por tecnologias de captura de CO2 pela fotossíntese, demonstra potencial significativo como um vetor de energia limpa no cenário de descarbonização.

Palavras-chave: Gaseificação de biomassa. Redução de emissões de carbono. Energia sustentável. Transição energética. Captura e armazenamento de CO_2.

LIST OF ILLUSTRATIONS

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LIST OF ABBREVIATIONS

LPG - Liquefied petroleum gas

LNG - Liquefied natural gas

Gasification-WGS - Eucalyptus gasification and the water-gas shift reaction

SMR-CCS - Steam methane reforming of natural gas with integrated carbon capture and storage

WGS - Water-gas shift

SCWG - Supercritical water gasification

PSA - Pressure swing adsorption

GHG - Greenhouse gas

SMR - Steam methane reforming

CCUS - Carbon Capture, Utilization, and Storage

CCS -Carbon capture and storage

CLR - Chemical looping reforming

ATR - Autothermal reforming

POX -Partial oxidation

MDEA - Methyl diethanolamine

MEA - Monoethanolamin

DGA - Diglycolamine

AMP - 2-amino-2-methyl-1-propanol

DEA - Diethanolamine

DIPA - Diisopropanolamine

MMEA - N-methylethanolamine

TEA - Triethanolamine

DFB - Dual fluidized bed

LOHC – Liquid organic hydrogen carrier

LCA - Life cycle assessment

LCI - Life cycle inventory

LCIA - Life cycle impact assessment

SUMMARY

PART 1: INITIAL CONSIDERATIONS

1. INTRODUTION

In the 20th century, oil and its derivatives dominated the global energy landscape, driving the exponential growth of the automotive and petrochemical industries. However, the intensive exploitation of these resources not only revealed the finite nature of fossil reserves but also highlighted severe environmental consequences, such as global warming and the increase in greenhouse gas emissions. In response, environmental policies began to emerge to mitigate these impacts and promote sustainable energy sources capable of meeting the world's growing energy demand (DA SILVA et al., 2021).

The 2022 United Nations Climate Change Conference (COP27) reinforced the urgent need to accelerate the global energy transition, emphasizing the role of renewable energy in achieving the target of limiting global temperature rise to 1.5°C by the end of the century. In this context, renewable hydrogen stands out as a promising alternative to decarbonize energy-intensive industrial and energy sectors, significantly contributing to the reduction of global emissions.

Among the main sustainable hydrogen production pathways, biomass gasification and steam methane reforming (SMR) coupled with carbon capture and storage (CCS) have emerged as key technologies. Both pathways hold significant potential for reducing greenhouse gas emissions and meeting global climate targets while contributing to the diversification of the energy mix.

Eucalyptus gasification presents itself as a sustainable solution in Brazil, owing to the widespread availability of this renewable resource and its carbon sequestration benefits during the cultivation of planted forests. On the other hand, SMR combined with CCS demonstrates great potential for emission reductions, particularly in regions where natural gas is abundant.

This study aims to assess the environmental impacts of these two renewable hydrogen production pathways within the Brazilian context, focusing on eucalyptus gasification and SMR. Life Cycle Assessment (LCA) methodologies are employed to quantify carbon emissions and other environmental impacts associated with these technologies, providing valuable insights into their potential environmental benefits.

1.1. Justification and Relevance of the Study

Brazil, as a global leader in renewable resources, is uniquely positioned to excel in the production of sustainable hydrogen, particularly through technologies such as eucalyptus gasification and steam methane reforming. The abundance of lignocellulosic biomass, coupled with the growing demand for low-carbon energy solutions, provides the country with a strategic opportunity to lead the renewable hydrogen market.

The relevance of this study is underscored by international commitments, such as those discussed at COP27, which promote the concept of a "clean energy mix," combining renewable energy sources with "low-emission" technologies. This approach is especially relevant to Brazil, which boasts an abundant supply of biomass and a well-established natural gas infrastructure, enabling diversified and locally adaptable energy solutions.

Against this backdrop, this study aims to assess the environmental impact of eucalyptus gasification and steam methane reforming technologies, focusing on their potential to reduce greenhouse gas emissions and contribute to the country's energy transition.

2. THEORETICAL FRAMEWORK

2.1.Overview of Brazil's investment in hydrogen production

Hydrogen is emerging as a key driver in the global reduction of greenhouse gas (GHG) emissions. As nations worldwide intensify efforts to mitigate the impacts of climate change and accelerate the transition to more sustainable energy alternatives, hydrogen stands out as a versatile and promising solution capable of meeting diverse energy and industrial demands (HAMMI et al., 2024).

In Brazil, Petrobras plays a significant role in the hydrogen sector as a self-producer, with its hydrogen production directed entirely toward internal consumption, primarily in oil refining processes. The production of gray hydrogen, obtained via steam methane reforming (SMR), has remained stable over the past few years, with an annual average of approximately 400,000 tons. Alternatively, Petrobras also utilizes naphtha as a feedstock in catalytic reforming (CR) processes, depending on operational requirements (Figure 1).

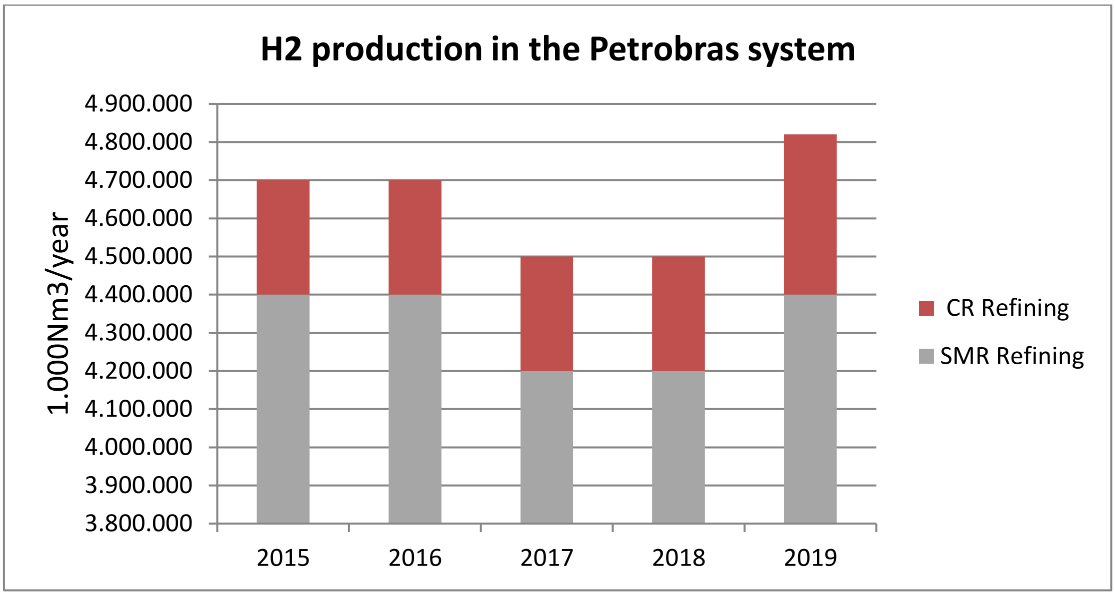

Figure 1. Hydrogen production in Petrobras' system (Source: GIZ, 2021).

The hydrogen produced is essential in Petrobras' refining chain, where it is used in hydrotreatment processes for gasoline, diesel, and lubricants. These processes are critical for meeting product quality requirements, such as reducing sulfur content and other impurities, complying with environmental regulations and improve the performance of final products (GIZ, 2021).

In the Brazilian context, the country stands out as a potential leader in green hydrogen production, thanks to its predominantly renewable electricity matrix (87% from clean energy sources) and the broad application of hydrogen in sectors such as food production, fertilizers, and low-carbon fuels. The development of this market relies on targeted investments, such as the R$ 42 million invested by EDP do Brasil in a hydrogen plant in Ceará, expected to begin operations in 2023, and Unigel's facility in Camaçari (Bahia), which aims to produce 10,000 tons of green hydrogen and 60,000 tons of green ammonia annually by 2025 (FERNANDES et al., 2023). Although the Unigel project has faced some delays, the company is actively moving forward with its plans and has announced additional investments of US$ 1.5 billion by 2027 to expand its green hydrogen production capacity in Camaçari, with the first phase already under construction

Currently, most hydrogen production plants in Brazil are expected to be situated in coastal regions, strategically positioned near the gas pipeline network, which would facilitate an efficient supply of raw materials. These plants are projected to be primarily operated by four major industrial gas companies, as outlined in Table 1 (OLIVEIRA, 2022). This strategic location and operational structure would provide a solid foundation for future investments in the development of new hydrogen production facilities.

Table 1. Hydrogen supply in Brazil (Source: GIZ, 2021)

Company	Revenue	Country of origin	Brazil representation	State
Linde AG	US$ 27 billion	Germany	White Martins	Rio de Janeiro
Air Liquide	€ 20 billion	France	Air Liquide	São Paulo
Air Products	US$ 8,9 billion	United States	Air Products	São Paulo
Messer	€ 2,8 billion	Germany	Messer	Barueri, São Paulo

2.2.Hydrogen production process and classification

Hydrogen in its molecular form can be derived from a variety of resources, including fossil fuels, biomass, and water (Figure 2). Obtaining pure hydrogen requires an energy-intensive separation process to dissociate hydrogen atoms from the other elements with which they are combined. This separation can be achieved through specific industrial processes or as a byproduct in various industrial operations, where H_2 is collected and purified (MEGIA et al., 2021).

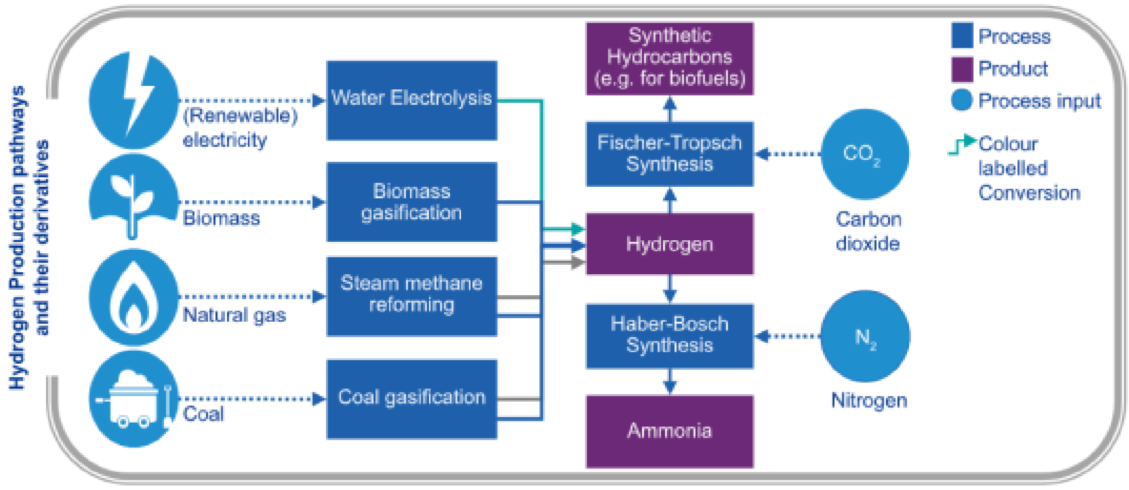

Figure 2. Hydrogen production process and use (Source: Empresa de Pesquisa Energética, 2022)

Hydrogen is considered a sustainable energy source since its production primarily relies on renewable energy sources. The production process of blue hydrogen is identical to that of gray hydrogen: both are produced from natural gas, predominantly through steam methane reforming (SMR), with CO_2 as a byproduct. The difference between these routes lies in the additional CCUS (Carbon Capture, Utilization, and Storage) steps incorporated into the blue hydrogen process (Empresa de Pesquisa Energética, 2022). These same technologies, namely SMR and CCUS, are also applicable when methane is derived from renewable sources, which, in turn, constitutes one of the production pathways for turquoise hydrogen. Table 2 presents the classification of hydrogen by color.

Table 2. Classification of Hydrogen by Color *(*Source: Garcia and Carvalho, 2022)

Color	Process
Black	Coal gasification (anthracite), without CCUS
Brown	Coal gasification (bituminous coal), without CCUS
Gray	Steam methane reforming (SMR) of natural gas, without CCUS
Blue	Steam methane reforming (SMR) of natural gas, with CCUS
Green	Water electrolysis using renewable energy sources (mainly solar and wind)
White	Extraction of natural or geological hydrogen
Turquoise	Methane pyrolysis, without generating CO_2
Moss	Catalytic reforming, gasification of residual plastics, or anaerobic digestion of biomass/biofuels
Pink	Water electrolysis using nuclear energy

2.2.1. Steam Methane Reforming Technology

According to Kokka et al., (2020), hydrogen can also be produced through the steam reforming of light alkanes (methane, propane, butane) and oxygenated compounds (methanol, ethanol, dimethyl ether) with high yields. Among these compounds, propane (C3H8) is of particular interest for hydrogen production because it can be liquefied at ambient temperature and a pressure of approximately 9 bar, allowing for easy storage and transport, as well as ready availability through the existing liquefied petroleum gas (LPG) infrastructure. Figure 3 illustrates the steam reforming process of methane, highlighting the key reactions and conditions involved in hydrogen production.

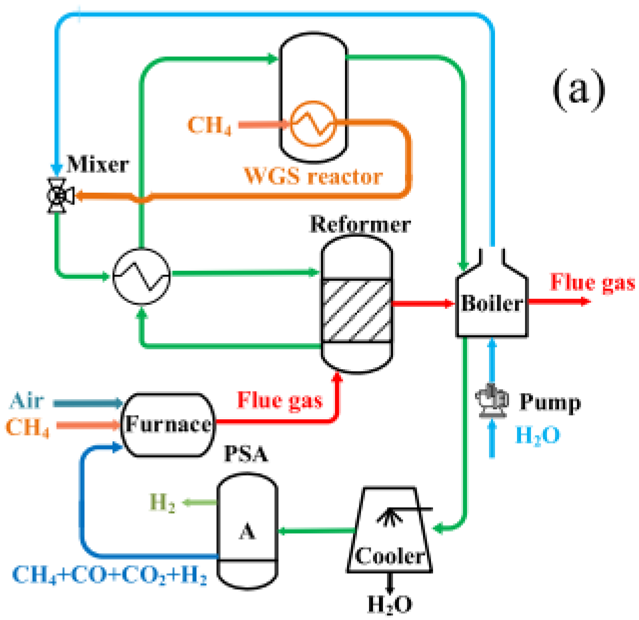

Figure 3. Process of SMR (Source: SONG et al., 2025)

Steam methane reforming typically involves a catalytic reaction in a tubular reactor at high temperatures, where hydrocarbons react with water to produce syngas, a mixture of hydrogen and carbon monoxide, along with some carbon dioxide (VILLAÇA, 2018). Methane reacts with water vapor at pressures between 3 and 25 bar and temperatures ranging from 700°C to 1000°C in the presence of a catalyst, producing hydrogen, carbon monoxide, and small amounts of carbon dioxide, as shown in Equation (1):

$$CH_4 + H_2O\ (+heat) \rightarrow CO + 3H_2 \qquad \text{Eq. (1)}$$

Due to the endothermic nature of this reaction, energy must be supplied in the form of heat to raise the temperature of the reactants, particularly water, to produce superheated steam. Increasing the temperature is crucial to enhance the yield and conversion rate of the reactants, improving the process efficiency. However, this requires elevated operational costs due to higher energy consumption.

To reduce operational costs, industries can seek ways to optimize the process, improve energy efficiency, and recover part of the heat generated by the reaction. Strategies such as using advanced catalysts and implementing heat recovery systems can help mitigate the costs associated with the endothermic steam reforming reaction (EMPRESA DE PESQUISA ENERGÉTICA, 2022).

Carbon monoxide then reacts with water vapor in an exothermic reaction, using a catalyst, producing additional hydrogen and carbon dioxide in what is known as the water-gas shift (WGS) reaction. The high temperatures of the reformer, however, are not favorable for this reaction (Table 4). The WGS reaction is commonly employed during the gas purification stage, serving to remove CO and maximize H_2 production, as shown in Equation (2):

$$CO + H_2O \rightarrow CO_2 + H_2\ (+heat) \qquad \text{Eq. (2)}$$

In this process, gas cleaning is performed to prevent contamination of the catalyst, after which the gas is directed to a reformer reactor, where it is mixed with water vapor to produce CO, CO_2, and H_2 gases. Subsequently, water vapor or condensate is added to the produced gases to increase the partial pressure of water, converting about 90% to 95% of CO into CO_2. This allows for higher H_2 production with the aid of an iron oxide-based catalyst (FILHO, 2022).

Once these aspects are considered and minimized, steam methane reforming produces a hydrogen-rich gas, along with smaller amounts of carbon dioxide, carbon monoxide, and methane. Since the hydrogen is mixed with other compounds, a separation step is required for its purification. In hydrogen production plants, purification is typically performed using pressure swing adsorption (PSA), which can produce up to 99.999% pure hydrogen with a recovery rate of 70% to 95% (MEGIA et al., 2021).

2.2.2. Factors influencing steam methane reforming

a) Temperature

The analysis of Gibbs free energy is a thermodynamic approach used to predict whether a chemical reaction is spontaneous under specific conditions. According to Figure 3, Gibbs free energy is employed to understand how temperature affects the conversion and equilibrium of reactions involving methane (CH_4), water (H_2O), and carbon dioxide (CO_2).

As expected, below 500°C, the conversion of CH_4, H_2O, and CO_2 is not significant. This suggests that the chemical reaction occurs at a limited rate at lower temperatures. At higher temperatures, equilibrium methane (CH_4) conversions of approximately 95% can be achieved. This indicates that the methane conversion reaction is favored at elevated temperatures.

Table 3. Articles on hydrogen production via steam reforming of natural gas (Source: Adapted by the Author, 2023)

Authors	Pressure (Bar)	Temperature (°C)	Reaction heat (kJ/mol)	CO_2 emissions (kg H_2)
(FILHO, 2022)	10 – 50	700 – 800	+ 206 -41	9
(COSTA, 2012)		700 – 1000		
(EMPRESA DE PESQUISA ENERGÉTICA, 2022)		650 – 900	+ 206 -41	7,62 – 9,13
(CHACON et al., 2016)	10 – 30	675 – 1000	+ 206 -41	
(SCHULTZ; EMERSON LÉO; SOARES; ITÂNIA PINHEIRO, 2014)		900	+ 206 -41	

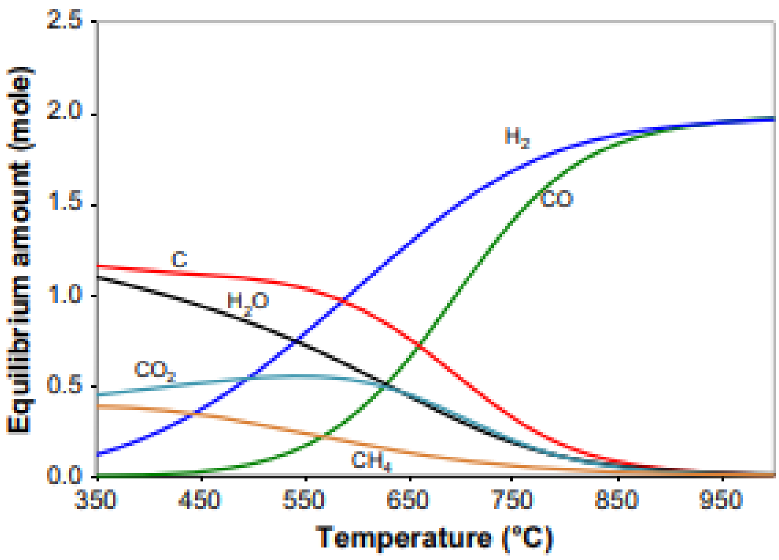

Figure 4. Effects of temperature on dry methane reforming (Source: Gao et al., 2011)

At lower temperatures, the amount of carbon (*C*) and water (H_2O) formed increases, which influences the CO/H_2 ratio at equilibrium. The CO/H_2 ratio is important in reforming reactions, especially in the production of synthesis gas.

To achieve high conversions and high selectivity for H_2 and *CO*, reforming reactions require high temperatures. This occurs because, as the temperature increases, the presence of CH_4 decreases, and more *CO* is present in the equilibrium gas.

b) Pressure

All reactions involved in methane reforming are volume-expansion processes, which means that increasing the pressure is unfavorable for these reactions. Consequently, as the pressure increases, the amount of products at equilibrium decreases significantly, as illustrated in Figure 5.

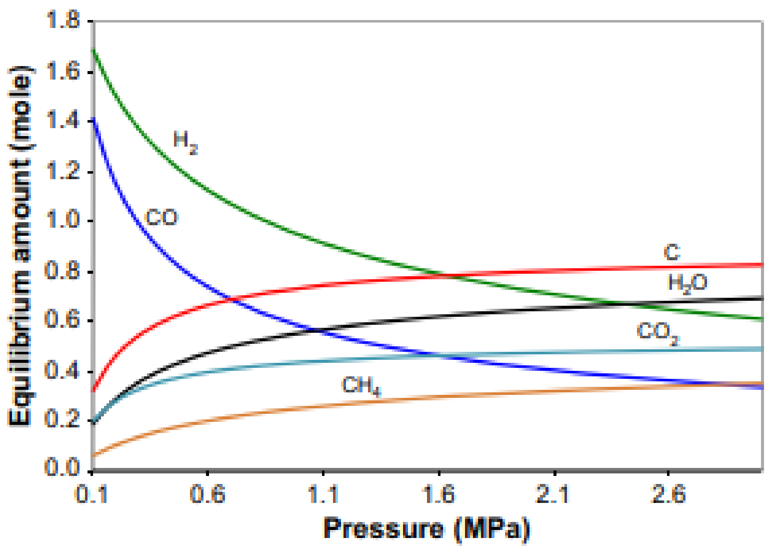

Figure 5. Effects of pressure on dry methane reforming (Source: Gao et al., 2011)

c) Molar Ratio

The formation of the products in dry reforming reactions is similar to steam reforming, meaning that CO and H2 occur in greater amounts across a wide range of CO_2/CH_4 molar input ratios at a temperature of 750°C, as shown in Figure 6. However, it is important to note that when the molar input ratio of CO_2/CH_4 exceeds 1.5 moles, the CO/H_2 ratio increases significantly. The excess CO_2 enhances the methane conversion, and as the CO_2/CH_4 ratio increases, the amount of hydrogen decreases due to the increased formation of water by-products (REYNER PARREIRAS PEREIRA DE OLIVEIRA, 2021).

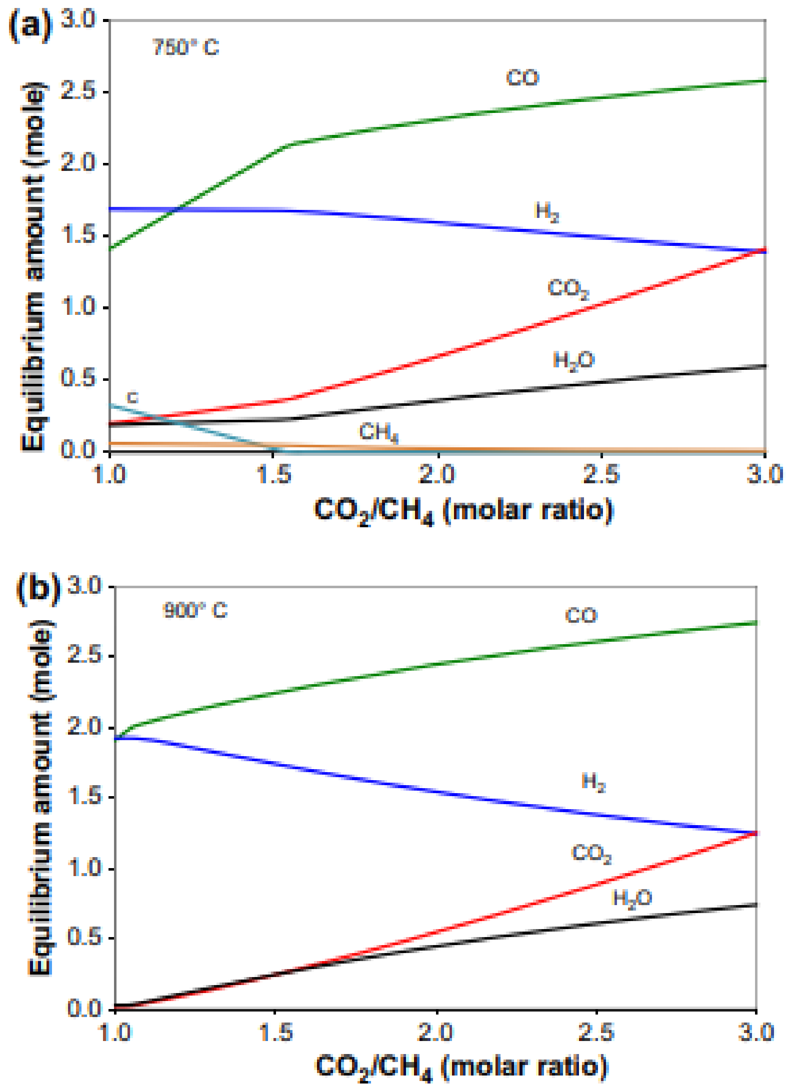

Figure 6. Effect of the *CO_2/CH_4* molar ratio in dry reforming a) 750ºC b) 900ºC (Source: Gao et al., 2011)

2.3. Natural gas as an energy carrier

Natural gas, used as the primary raw material, contributes to total emissions in fuel production due to gas recovery and processing. In the LNG supply chain, the first step is the liquefaction of natural gas. The primary source of emissions during this production phase is the fuel consumption for operating equipment, which involves the use of electricity and gas losses through venting, resulting from pipeline and equipment failures. After production, LNG is stored in specific tanks located at the production site before being transported by ocean-going tankers (AL-BREIKI; BICER, 2021).

2.4. Grey Hydrogen

As described by Hammi et al. (2024), hydrogen production varies in environmental footprint. Grey hydrogen is produced on a large scale through processes involving the reforming of fossil fuels, employing specific techniques such as autothermal reforming (ATR), steam methane reforming (SMR), or natural gas reforming, as well as partial oxidation (POX) of heavy oil or coal. Grey hydrogen, produced by methane reforming, generates 11.57 kg of CO_2 equivalent per kg of hydrogen.

The grey hydrogen production system using the SMR technique starts with the pretreatment of raw natural gas (Figure 7). During this phase, sulfur compounds are converted into H_2S by hydrogenation, and the H_2S is removed using a *ZnO* bed. After pretreatment, natural gas and steam are fed into a steam reformer, where they are converted into synthesis gas and hydrogen. The resulting gases then pass through a high-temperature shift reactor (HTS) and a low-temperature shift reactor (LTS), where synthesis gas is further transformed into hydrogen and additional CO_2. Hydrogen is separated from CO_2 with the aid of a pressure swing adsorption (PSA) unit. The PSA unit generates a residual gas, which is recycled and used as a heat source for the steam reformer. The final product is hydrogen with 99.95% purity (Hren et al., 2023).

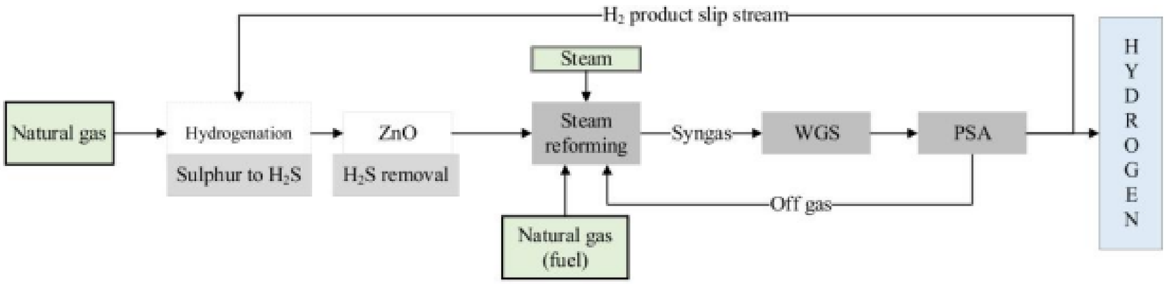

Figure 7. Grey hydrogen production technology (Source: Hren et al., 2023)

2.5. Blue Hydrogen

The production of hydrogen from methane reforming with carbon capture and storage (CCS), known as blue hydrogen, involves the implementation of a Carbon Capture & Storage system, aimed at separating the CO_2 generated during the process for later permanent geological storage. This procedure can be carried out in either a Steam Methane Reforming (SMR) reactor or an Autothermal Reforming (ATR) reactor. The carbon intensity of the resulting hydrogen varies significantly depending on the fraction of CO_2 capture applied, as discussed in the study by Cownden, Mullen and Lucquiaud, (2023). Figure 8 illustrates the scheme of the blue hydrogen production technology, detailing the key stages of the process and the role of CCS in reducing emissions.

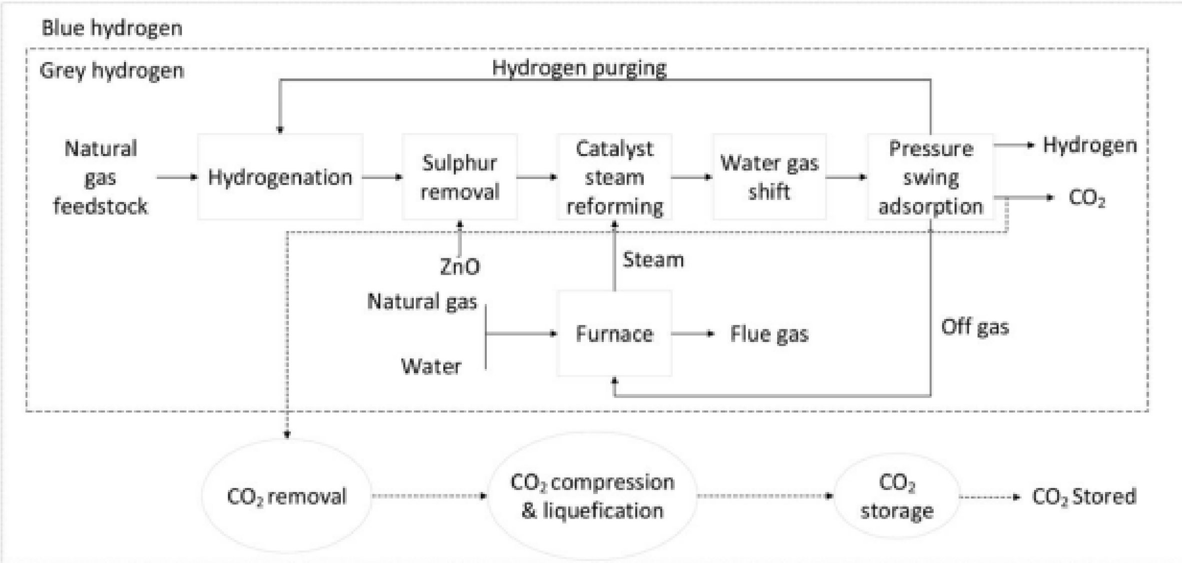

Figure 8. Blue hydrogen production technology (Source: Patel et al., 2024)

According to Zang, Graham and Mallapragada, (2024), the integration of the hydrogen production process with CCS technologies uses methyl diethanolamine (MDEA) between the WGS and PSA to capture 95% of the CO_2 from the hydrogen-rich gas produced by the WGS reactors. In the MDEA capture process, the hydrogen-rich gas passes through an amine tower to absorb CO_2 at 44°C, producing CO_2-poor gas that flows to the PSA for hydrogen purification. Meanwhile, the CO_2-rich amine from the absorber is sent to a stripper column to separate CO_2 and regenerate the lean amine solution.

This technology significantly reduces greenhouse gas emissions (GHGs) and their impact on global warming. A study showed that with a 56% CO_2 capture rate, the overall global warming impact decreases to 6.87 kg of CO_2 eq/kg of hydrogen, with 60.0% of it coming from emissions related to the processes. Higher capture rates, such as 90%, further reduce the impact to 3.97 kg of CO_2 eq/kg of hydrogen, decreasing the contribution of process-related emissions to 24.9%. Blue hydrogen shows only an 18–25% reduction in greenhouse gas emissions compared to gray hydrogen (Hammi et al., 2024).

2.6. Biomass Gasification

The main method of producing hydrogen from biomass is through thermochemical routes, including steam gasification, supercritical water gasification, and fast pyrolysis, as illustrated in Figure 9. Compared to pyrolysis, gasification is recognized as more promising for industrial production due to its higher efficiency and hydrogen yield.

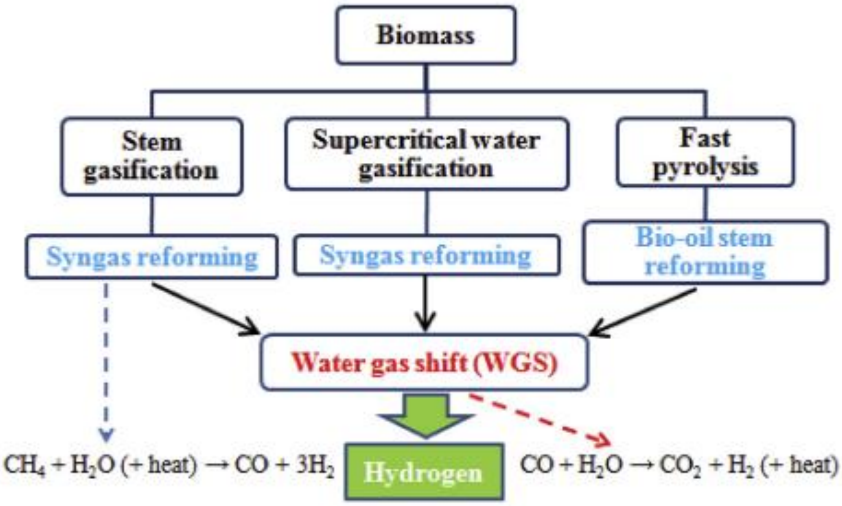

Figure 9. Thermochemical routes for biomass-based H_2 production. (Source: Cao et al., 2020)

According to Barbuzza et al., (2019), the growing interest in biomass for energy production, beyond direct combustion, is due to its wide availability, CO_2 neutrality, and lower sulfur emissions compared to fossil fuels. Biomass gasification produces syngas, a mixture of H_2 and *CO*, which can be burned in thermal power plants more efficiently and cleanly than biomass directly.

Syngas is a mixture of gases comprising hydrogen, carbon monoxide, methane, carbon dioxide, water vapor, and nitrogen in varying proportions. A series of chemical reactions are involved in the production of these gases. These reactions occur in a gasifier at temperatures between 800 °C and 1000 °C (NWOKOLO; MUKUMBA; OBILEKE, 2020).

Hydrogen production from biomass gasification begins with pre-drying, reducing its moisture content to below 5% at temperatures between 100 °C and 200 °C. Common heat sources for this drying process include hot air and steam. Although hot air drying efficiency increases at higher temperatures, elevated temperatures also release volatile compounds that complicate air purification. Therefore, the ideal temperature range for drying is between 100 °C and 130 °C (ZHAO; TAMADON; PONS, 2022).

According to Nwokolo, Mukumba, and Obileke (2020), within the gasifier, biomass gasification occurs simultaneously in four main stages: drying, pyrolysis, oxidation, and reduction.

- Drying: The biomass moisture content is vaporized at approximately 200 °C.
- Pyrolysis: The biomass is decomposed into solid residues and volatile compounds at temperatures between 200 °C and 600 °C, breaking down cellulose, hemicellulose, and lignin.
- Partial Oxidation: Volatile compounds and solid residues (charcoal) are converted into CO, CO_2, and H_2O at temperatures above 700 °C.
- Reduction: At temperatures above 800 °C, volatile compounds and charcoal react with oxidizing agents to produce CO, H_2, and CH_4.

The raw syngas is processed in a reformer, where tar and light hydrocarbons are converted into CO and H_2. The burned charcoal generates heat or combustion gas, which is used to dry the biomass. After reforming, the raw syngas passes through a scrubber and a liquid oxidation catalyst unit to remove remaining particles and H_2S. The clean gas then undergoes the Water-Gas Shift (WGS) reaction, which produces hydrogen and CO_2. Before being released from the system, hydrogen is purified by a Pressure Swing Adsorption (PSA) unit, which removes CO_2 and provides high-purity hydrogen (Figure 10). The residual gas is treated in a two-stage polymer membrane separation process to capture CO_2 and reduce the greenhouse gas footprint (Hren et al., 2023).

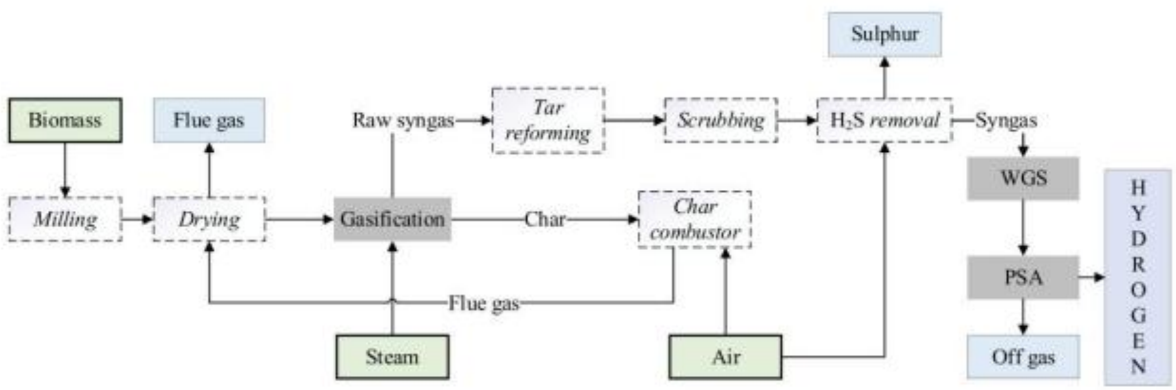

Figure 10. Biomass gasification hydrogen production technology (Source: Hren et al., 2023)

In addition, the reforming (Eq.7) and water-gas shift reactions (Eq.8) can occur in the same reactor, saving energy. Supercritical water gasification increases hydrogen production but requires high pressure and temperature, which can be expensive without catalysts. Supercritical water catalytic gasification is promising, as it improves efficiency by reducing activation energies and accelerating reactions while maintaining catalyst stability under extreme conditions (BORGES et al., 2020).

According to Yao et al., (2017), the use of olivine as a bed material and heat carrier demonstrated catalytic activity that enhances gasification reactions and consequently reduces the tar content of the produced gas. Afterward, the obtained gas is cooled, filtered, and introduced into a fixed bed, using a Fe/Cr-based catalyst, where CO and H_2O are converted into H_2 and additional CO_2, according to the exothermic WGS reaction.

Therefore, Kargbo, Ng and Phan, (2022) integrated two-stage gasification, resulting in the complete conversion of all elements of the biomass feedstock into high-quality syngas. It also offered other advantages, such as utilizing CO_2 released from pyrolysis as an oxidizing agent to react with volatiles (via dry reforming) and carbon in the charcoal fraction (via the Boudouard reaction, Eq. 5). The gasification reactions are presented in Table 4.

Table 4. Gasification Reaction Stages (Source: Brito et al., 2023).

Homogeneous Reactions	**Reaction Equation**		**Equation number**
Combustion	$C + 1/2O_2 \rightarrow CO$	-111 MJ/kmol	Eq. (3)
	$CO + 1/2O_2 \rightarrow CO_2$	- 283 MJ/kmol	
	$H_2 + 1/2O_2 \rightarrow H_2O$	-242 MJ/kmol	
Methane Reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206 MJ/Kmol	Eq. (4)
	Heterogeneous Reactions		
Boudouard	$C + CO_2 \leftrightarrow 2CO$	+172 MJ/Kmol	Eq. (5)
Water-Gas Reaction	$C + H_2O \leftrightarrow CO + H_2$	+131 MJ/kmol	Eq. (6)
Methane Formation	$C + 2H_2 \leftrightarrow CH_4$	-75 MJ/Kmol	Eq. (7)
WGS	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41 MJ/Kmol	Eq. (8)

2.7. Carbon Capture, Utilization, and Storage (CCUS) Technology

The main CCUS technologies consist of four stages: capture, transportation, utilization, and storage of CO_2.

2.7.1. CO_2 Capture

CO_2 sources are diverse, and the capture technology can generally be divided into five types: pre-combustion, post-combustion, oxy-combustion, industrial processes, and direct air capture, all of which aim to separate CO_2 from exhaust gases, as illustrated in Figure 11.

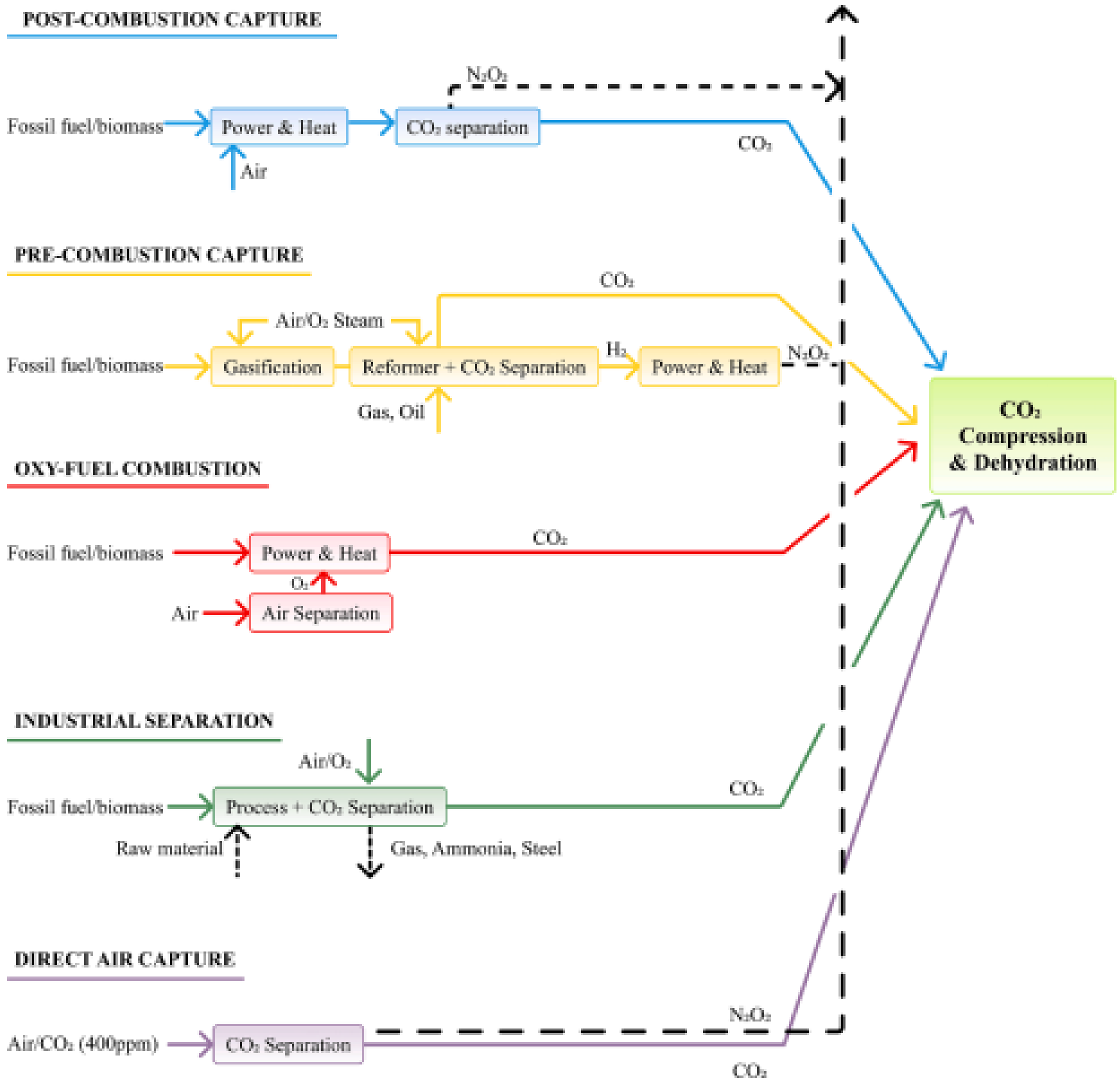

Figure 11. CO_2 Capture Systems (Source: Dziejarski, Krzyżyńska and Andersson, 2023)

a) Pre-combustion

The pre-combustion capture route coupled with power plants has the main advantage of enabling the co-production of energy and hydrogen through steam methane reforming or fossil fuel gasification. A representative scheme of a hydrogen plant starts with a reformer or gasifier where syngas is produced, followed by a water-gas shift reformer (WGS) where carbon monoxide from syngas reacts with water vapor to produce CO_2 and more hydrogen. The resulting product stream is sent to the acid gas removal section, containing a system for hydrogen-rich separation (HOSPITAL-BENITO et al., 2022).

b) Post-combustion

This involves separating CO_2 from other products contained in the combustion gas mixture, such as nitrogen, sulfur dioxide, and nitrogen oxides, primarily due to the inability to sequester combustion gases, considering the costs of their compression and storage (DZIEJARSKI; KRZYŻYŃSKA; ANDERSSON, 2023).

CO_2 is separated after combustion in the presence of atmospheric air, where a low-pressure gas mixture containing diluted CO_2 (typically below 15% concentration) is removed from the exhaust gases. Several technologies can perform this separation, but in general, they involve high costs and energy consumption (EMPRESA DE PESQUISA ENERGETICA, 2022).

Post-combustion capture can be performed through chemical absorption, adsorption, membrane separation, or low-temperature separation, with chemical absorption being the most commonly used. This method involves the use of alkaline absorbents that react with CO_2 to form salts through a reversible acid-base reaction. The ideal absorbent should have fast absorption, low energy consumption for regeneration, and low corrosion, making the choice of absorbent crucial. Solvents like monoethanolamine (MEA) and ammonia are commonly used in carbon capture, with ammonia standing out due to its lower cost, lower corrosion, higher absorption capacity, and lower regeneration energy (YANG et al., 2023).

c) Oxy-combustion

This method uses atmospheric air, where fuel combustion is carried out with pure oxygen. In this case, the complexity of the capture stage is transferred to oxygen production, which becomes simpler. Oxygen is typically produced from air purification through cryogenic separation, also incurring high costs and energy consumption (EMPRESA DE PESQUISA ENERGETICA, 2022).

This capture method has the advantages of reducing combustion gas emissions and nitrogen gases, along with improving the energy conversion efficiency of the boiler and enabling direct CO_2 sequestration. The CO_2 concentration in the resulting combustion gas mixture can reach 80–98%, depending on the fuel, combustion process, air leakage levels, oxygen purity, and excess (DZIEJARSKI; KRZYŻYŃSKA; ANDERSSON, 2023).

d) Industrial Processes

This capture system requires the removal of CO_2 from a gas stream or simpler processes, such as CO_2 capture from fermentation for ethanol production (Energetic Research Company, 2022).

e) Direct Air Capture

The direct removal of CO_2 from ambient air has recently gained significant attention from researchers due to its potential to minimize the issues associated with transporting large volumes of CO_2 from point sources to suitable geological sequestration sites, reducing atmospheric CO_2 concentration (AL-MAMOORI et al., 2017).

2.7.2. CO_2 Capture Technologies

According to Dziejarski, Krzyżyńska, and Andersson (2023), CO_2 capture involves the separation of carbon dioxide from the gases resulting from the combustion of fossil fuels and biomass. Several technologies are used for this, including absorption, adsorption, membranes, cryogenic distillation, and solid looping processes (including calcium looping and chemical looping combustion). This step is critical in the CO_2 capture and storage (CCS) process, as combustion gases often contain additional pollutants such as H_2S, CO, CH_4, SOx, and water vapor. These pollutants can alter the physical and chemical characteristics of the gas stream, affecting the efficiency and cost of storage. Therefore, the presence of these pollutants is a crucial consideration for the effectiveness and economic viability of CCS technology, as illustrated by the key challenges and opportunities in Table 5.

Table 5. Key Challenges and Opportunities in CO_2 Capture Technology (Source: Al-Mamoori et al., 2017)

Technology	Challenges	Opportunities
Absorption	Equipment corrosion, degradation of amines, high energy demand for regeneration, and environmental impact from significant energy penalties	Improvement in commercially available absorption technologies using ionic liquids and advanced amines
Membranes	High energy consumption in post-	Hollow fiber membranes,

	combustion applications, high membrane production costs, unsuitability for high temperatures, and difficult balance between CO_2 purity and recovery	mixed matrix membranes, and cryogenic processes with hybrid membranes
Adsorption	Long-term stability against impurities and moisture, thermal management, pressure drop, and adsorbent attrition	Composite adsorbents, structured adsorbents, rapid cycling, hybrid membrane and PSA processes
Chemical Looping	Operation at high pressures, efficient and stable oxygen transport materials	Composite oxides as oxygen carriers, process design modifications
Direct Air Capture	Ultra-diluted CO_2 content, energy-intensive, and development of durable materials	Coupling with renewable energy sources and structured adsorbents
Hybrid Capture Processes	Less studied, synergy and process optimization improvements, development of hybrid materials	Membrane distillation, PSA, and hybrid pressure-temperature swing adsorption (PTSA) processes

2.7.3. CO_2 Transport

Regarding the transportation of *CO_2* between sources and storage sites, there are three main categories: by tank trucks, by newly constructed or refurbished pipelines, and by ships (JIANG; ASHWORTH, 2021). Table 6 illustrates the main advantages and disadvantages of these transportation methods.

Table 6. Main advantages and disadvantages of *CO_2* transportation techniques (Source:(DZIEJARSKI; KRZYŻYŃSKA; ANDERSSON, 2023)

Transportation Type	Advantages	Disadvantages
Rail	Not affected by weather or traffic, and no need for specialized railway infrastructure.	Both the CO_2 source and destination must adhere to strict standards and must be located near the railway.
Road	Not limited by the CO_2 source or destination, and no need for financial investments in building new transportation infrastructure.	Transportation expenses are significant; labor is susceptible, and fuel is quite expensive.
Pipelines	Large transport capacity and relatively low transportation costs.	Pipeline infrastructure requires a significant initial financial commitment.
Ships	Good economics, and transportation technology has reached a mature state.	Strict standards are imposed on transport equipment regarding temperature and pressure regulations.

2.7.4. CO_2 utilization

CO_2 utilization refers to its application for productive purposes, serving as an alternative for the allocation of emissions captured in blue hydrogen plants. The process must be economically viable, safe, and environmentally sustainable. The primary utilization pathways can be categorized as enhanced oil or gas recovery, chemical conversion, mineralization, and desalination (AL-MAMOORI et al., 2017).

The two main forms of *CO_2* utilization involve direct use and conversion into other products. While the direct use of *CO_2* has established and promising applications, its potential scale is limited. Conversely, *CO_2* conversion offers a wide range of opportunities, including the production of fuels, chemicals, and construction materials. This can be achieved through biological pathways, such as photosynthesis and microbial fixation, and chemical pathways, which include methods like reforming, hydrogenation, carboxylation, mineralization, electrochemistry, photochemistry, and plasma catalysis, as illustrated in Figure 12 (EMPRESA DE PESQUISA ENERGETICA, 2022).

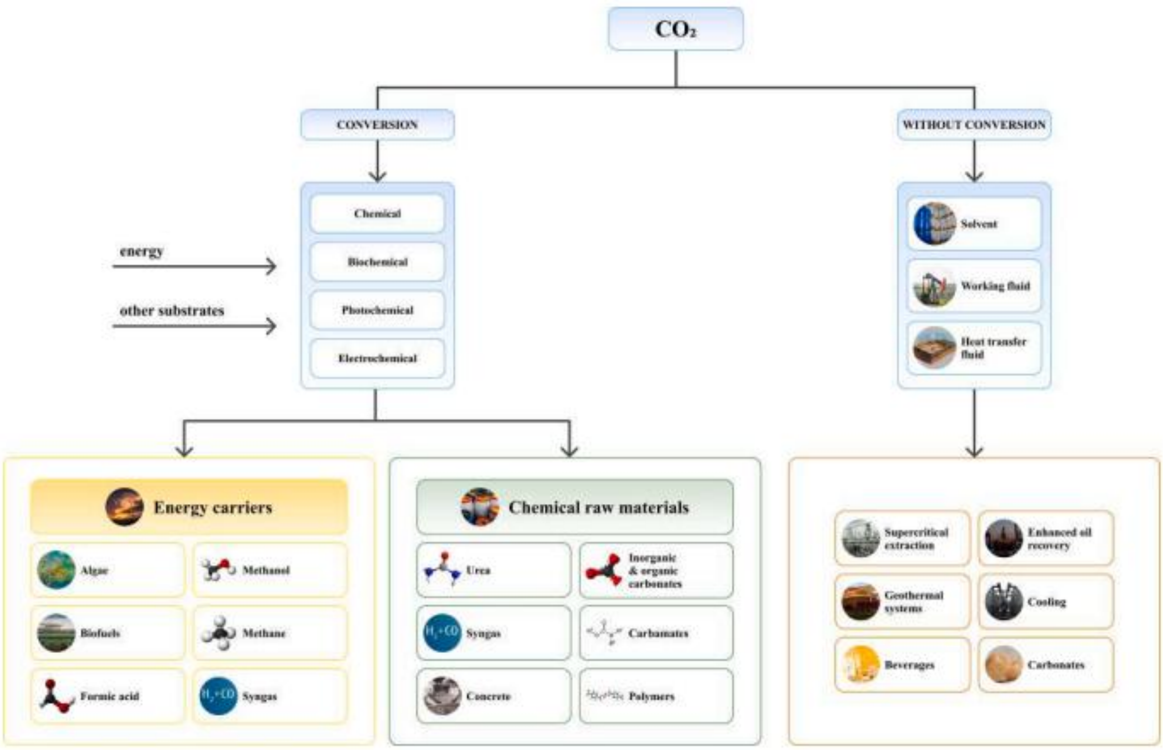

Figure 12. Forms of CO_2 utilization and reuse (Source:Dziejarski, Krzyżyńska and Andersson, 2023).

2.7.5. Geological Storage of CO_2

Geological carbon storage encompasses all processes involved in capturing and storing carbon, where a relatively pure stream of CO_2 captured from stationary industrial and energy-related sources is conditioned for transportation (compressed, dried, and liquefied for ship transport), transported to the storage site, and injected into geological formations for long-term atmospheric isolation. In response to climate change, its use should be prioritized as the most effective and capable mitigation solution (ALKAN; BURACHOK; KOWOLLIK, 2023).

According to the Empresa de Pesquisa Energética (2022), the efficiency of CO_2 storage in a geological formation increases with the rise in CO_2 density, improving storage safety by reducing buoyancy forces. The temperature gradient, which varies depending on the reservoir depth, significantly influences CO_2 density. Sedimentary basins with lower temperatures would, therefore, be more favorable for CO_2 storage. Table 7 outlines the main methods of CO_2 storage.

Table 7. Status of Major CO_2 Storage Methods (Source: Dziejarski, Krzyżyńska, and Andersson, 2023)

Storage Method	Current Status
Saline Formations	Rapid CO_2 injection at a significant rate (1 Mtpa); injected CO_2 can be monitored, and storage is permanent; tools for identification and evaluation are well-established; low economic costs.
CO_2-EOR (Enhanced Oil Recovery)	Proven storage sites; maximizes oil recovery; more specific monitoring is required to ensure injected CO_2 is stored permanently.
CO_2-EGR (Enhanced Gas Recovery)	Proven storage sites; maximizes natural gas and gas condensate recovery; suitable for tight and low-permeability reservoirs.
Depleted Oil and Gas Fields	Technically mature; hermetic structures; limited capacity; applied only in demonstration projects.
Mineral Carbonation (Basaltic and Ultramafic Rocks)	High storage potential; safe and durable storage; rock permeability is difficult to predict; most conventional CCS tools cannot monitor CO_2 plumes in basalt.
CO_2-ECBM (Enhanced Coalbed Methane)	Viable technology and can increase methane production; methane generated provides revenue for operations; CO_2 injection significantly reduces coal permeability, increasing operational complexity and costs;

	applicable only to coal seams that will never be mined.
Ocean Storage	Currently prohibited by law; highly risky and unpredictable outcomes; in the conceptual formulation phase.

2.8.Hydrogen Storage and Transportation

Hydrogen storage can be carried out in gaseous, liquid, cryo-compressed, or solid forms. Regarding transportation, key considerations include available space and safety, which dictate the choice of hydrogen storage type.

Figure 13 illustrates the hydrogen storage and transportation schemes.

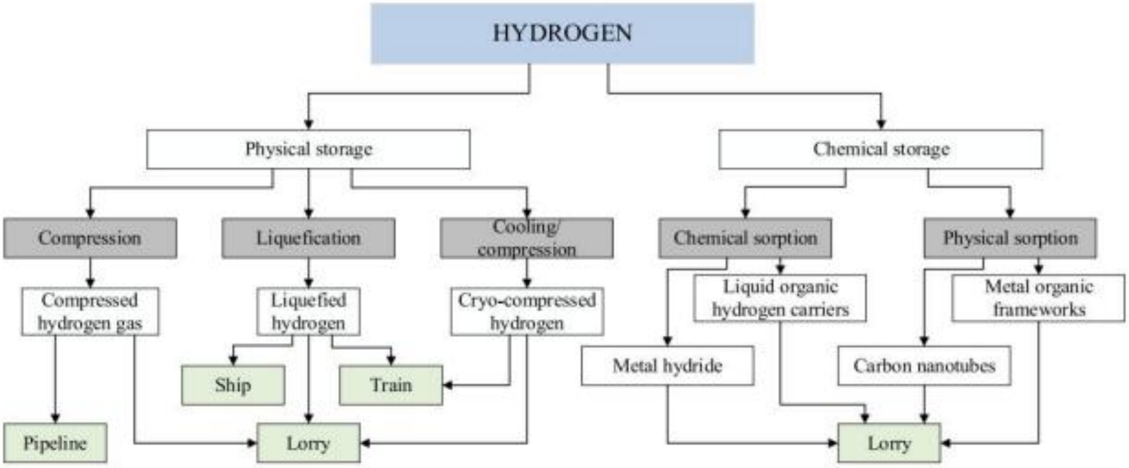

Figure 13. Hydrogen Storage and Transportation (Source: Hren et al., (2023)

Compressed hydrogen is stored in high-pressure tubular trailers, which are widely used due to their safety and well-established technology. These tubular trailers, consisting of a truck cab and hydrogen containers, are commonly utilized to transport hydrogen to refueling stations. To increase efficiency, the entire trailer can be exchanged at the station within approximately one hour. The number of trailers and trucks required depends on demand, capacity, transit time, and availability (RONG et al., 2024). Table 3 presents a comparison of various hydrogen transportation technologies.

Table 8. Comparison of Hydrogen Transportation Technologies *(Source:* Zhang et al., 2024)

Technology	Advantages	Disadvantages	Prospects

Tube trailers	Easy to deploy and scale, flexible routing	Limited capacity, higher transportation costs, and safety concerns due to high pressure	Improvements in materials and design to increase capacity and advanced safety features
Pipelines	Large capacity, low operating costs, and reliability	High initial investment, limited geographical reach, and susceptibility to leakage and sabotage	Expansion of pipeline networks, enhanced materials, and leak detection technologies
Liquid transportation	Higher energy density and established technology	Cryogenic storage and high energy consumption	Improved insulation materials, energy-efficient processes
Carrier-based Transportation	Ease of handling, transportation, and storage	Complex chemical processes and high energy demand	Advances in support materials and efficient release methods

Storing hydrogen in liquid form is an effective strategy to increase its energy density. The liquefaction process involves compressors, heat exchangers, expanders, and throttle valves, with the Linde and Joule-Thomson cycles being the primary methods used. In the Linde cycle, the gas is compressed, cooled, and expanded to become liquid, while the cryogenic process cools hydrogen to temperatures below -253°C, using gases such as helium, neon, and nitrogen. Liquid hydrogen offers superior energy density (70.9 g/L) compared to compressed gas (42 g/L). However, challenges such as liquid evaporation, leakage, and the need for coolers and insulating containers are significant. To mitigate energy losses, new approaches, such as cryo-compressed hydrogen storage, are being developed. This technique combines compression and cryogenics (FAYE; SZPUNAR; EDUOK, 2022).

The mode of transport for liquid hydrogen trucks differs from compressed hydrogen trailers. The liquid hydrogen tank and truck are typically inseparable and cannot be used as secondary storage equipment at hydrogen refueling stations. Therefore, the number of liquid hydrogen trucks is always equal to the number of tanks (Rong et al., 2024).

The cryo-compressed hydrogen storage method was developed to overcome the disadvantages of compressed and liquid hydrogen storage. It involves storing hydrogen at cryogenic temperatures in a pressurized container (250–350 atm). In contrast, cryogenic vessels maintain liquid hydrogen at ambient pressures. This method extends dormancy as vessel pressure increases, providing significant receptivity to heat. The cryo-compressed method requires a two-step process: compression and cooling (Faye, Szpunar, and Eduok, 2022).

Hydrogen transport using carriers facilitates handling, transport, and storage compared to gaseous or liquid hydrogen. Carriers include metal hydrides, ammonia, and hydrogen organic compounds, which can store and release hydrogen, offering an alternative approach (ZHANG et al., 2024).

The liquid organic hydrogen carrier (LOHC) method offers an innovative approach to hydrogen storage and transportation, binding hydrogen to the carrier via covalent bonding after a chemical reaction. This method presents advantages over high-pressure gaseous hydrogen storage or cryogenic liquid storage, which are more expensive and face challenges such as leaks or evaporation. On the other hand, the stable physical and chemical properties of liquid organic substances make this process more suitable for large-scale storage (RONG et al., 2024).

Solid-state hydrogen storage refers to storing hydrogen within a solid material, usually through chemical or physical bonds. It offers several advantages, including high volumetric and gravimetric energy density (depending on the material), safer storage due to reduced pressure requirements, and more compact storage options. However, this technology faces challenges such as complex material synthesis and handling, slow hydrogen absorption and release kinetics (depending on the material), and temperature sensitivity for some materials (Zhang et al., 2024).

2.9. Life cycle assessment (LCA)

LCA, initially defined in the United States in 1990, aims to evaluate the potential environmental implications of a product or system. This encompasses phases such as raw material extraction, manufacturing, use, and end-of-life disposal or recycling. LCA strives to provide a comprehensive and quantitative assessment of the ecological footprint of the product or system, considering all relevant environmental aspects, including but not limited to global warming potential, acidification potential, eutrophication potential, and resource depletion (Hammi et al., 2024).

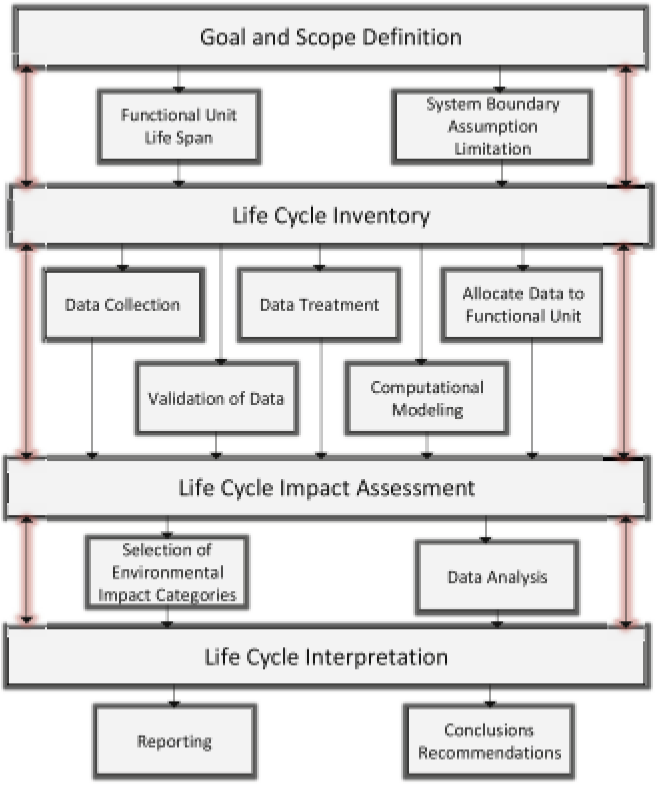

Figure 14. Life Cycle Assessment framework based on ISO 14040 (Source: Al-Breiki and Bicer, 2021).

According to Osman et al., (2024), ISO 14040 and 14044 define LCA as an environmental management tool that examines potential environmental impacts between a technical system (technological sphere) and the environment (from raw material production to the end-of-life of the process). The LCA process follows four main phases (Figure 14):

a) Goal and scope definition:

The scope of an LCA, including system boundaries and the level of detail, depends on the object and intended use of the study. The system boundary indicates specific processes that may be included or excluded after the procedure and is typically illustrated through input-output flow diagrams. The functional unit serves as a reference unit to provide normalizable inventory data. It is generally considered as an indicator of the product's volume, although it can also be affected by parameters such as energy, site area, distance, and economic significance.

b) Life cycle inventory (LCI):

This phase concerns the input/output data associated with the system under study. It involves collecting the necessary data to meet the objectives of the study in question.

c) Life cycle impact assessment (LCIA):

This phase provides additional information to help evaluate the LCIA results of a product system, aiming to better understand its environmental significance.

d) Life cycle Interpretation:

The results of an LCIA and/or an LCI, or both, are summarized and discussed as a basis for conclusions, recommendations, and decision-making according to the goal and scope definition.

2.10. Case studies on LCA of hydrogen production

Studies related to Life Cycle Assessment (LCA) are the focus of numerous researchers in the hydrogen production field, employing this methodology to analyze the environmental impacts of a product throughout its lifecycle.

Hammi et al. (2024) conducted a comprehensive review of Life Cycle Assessment (LCA), environmental impacts, and color analysis in hydrogen production. They highlighted key indicators for environmental impact assessment, such as Global Warming Potential (GWP), which measures a substance's contribution to global warming compared to carbon dioxide over a specific period, aiding in climate change mitigation. Other indicators include Acidification Potential, which evaluates a substance's ability to acidify soil, water, and vegetation; Eutrophication Potential, which assesses the nutrient enrichment impact on aquatic life; Abiotic Depletion Potential, which estimates the depletion of non-renewable resources; and Human Toxicity Potential, which evaluates damage to human health. The authors emphasized that CO_2 emissions in hydrogen production vary depending on the energy source used, with minimal emissions in water-based production chains but significant emissions in fossil fuel-based processes unless Carbon Capture, Utilization, and Storage (CCUS) technologies are applied.

a) Gray Hydrogen

In a comparative LCA study of the environmental impacts associated with technologies corresponding to gray, blue, turquoise, and green hydrogen, quantified through LCA methodology, Hermesmann and Müller, (2022) found that environmental impacts are largely determined by the underlying electricity and natural gas supply chains.

Matin and Flanagan, (2024) conducted an LCA to evaluate the environmental contributions of conventional and dry reforming of methane using non-thermal plasma for hydrogen production. The LCA considered midpoint impact categories such as acidification potential, carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, global warming potential, non-carcinogenics, ozone depletion potential, respiratory effects, and air pollution. Results indicated that the use of renewable energy sources can improve the environmental performance of dry reforming with non-thermal plasma. However, improvements in energy efficiency, reagent conversion, and hydrogen selectivity are still required. Cho, Strezov, and Evans (2022) assessed the impact of direct emissions from hydrogen production facilities in the United States, focusing on natural gas-based steam methane reforming (SMR) technology. The authors concluded that carbon dioxide emissions dominated the pollutants assessed and had an insignificant impact on global warming in terrestrial ecosystems compared to human health effects.

b) Blue Hydrogen

Mio et al., (2024) evaluated the sustainability of different hydrogen production processes and concluded that blue hydrogen, which combines gray hydrogen with carbon capture and storage (CCS), exhibits poorer environmental performance in almost all categories except global warming potential. Although CCS reduces CO_2 emissions, it demands additional materials and energy. Consequently, the authors suggest that gray hydrogen, despite its uncaptured CO_2 emissions, should still be considered in comparisons with other technologies such as green hydrogen.

On the other hand, (KHOJASTEH SALKUYEH; SAVILLE; MACLEAN, 2017) compared fossil fuel consumption in SMR options with and without CCUS, resulting in a 39% increase in fossil fuel consumption and global warming potentials (GWP) of 11.7 and 3.5 kg CO_2 eq per kg H_2, respectively.

Zang, Graham and Mallapragada, (2024) performed a techno-economic analysis and cradle-to-gate LCA of five hydrogen production scenarios, focusing on emissions characterization and cost implications of various CCS schemes. For the baseline SMR case, the largest greenhouse gas (GHG) emissions came from local boiler flue gas at 9.35 kg CO_2/kg-H_2, followed by upstream natural gas emissions at 2.18 kg CO_2/kg-H_2, while the smallest emissions came from U.S. grid electricity at 0.28 kg CO_2/kg.H_2. Compared to the baseline SMR case, CCS scenarios reduced GHG emissions by 63%–68%, even though carbon capture efficiency ranged from 94.6% to 99.5%. GHG emissions in the SMR-CCS case were 6.31 kg CO_2 eq/kg H_2 lower than the baseline SMR, with on-site emissions reduced by 8.97 kg CO_2 eq/kg H_2. However, upstream natural gas and electricity emissions increased by 0.14 kg CO_2 eq/kg-H_2 and 0.61 kg CO_2 eq/kg-H_2, respectively *c) Biomass gasification*

Regarding hydrogen production from renewable sources, Ganeshan et al., (2023) conducted a techno-economic assessment and LCA of biohydrogen production. Among the available techniques, gasification was deemed the most economical ($1.2/kg H_2), followed by anaerobic digestion ($1.25/kg H_2). Additionally, LCA results showed that hydrogen production through biomass gasification resulted in the lowest carbon footprint of -1.6 kg CO_2 eq./kg H_2.

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PART 2: COMPARATIVE LIFE CYCLE ASSESSMENT OF HYDROGEN PRODUCTION METHODS: EUCALYPTUS BIOMASS GASIFICATION VS. NATURAL GAS STEAM REFORMING IN BRAZILIAN CONDITIONS

ABSTRACT

A life cycle assessment (LCA) was applied to compare the production of hydrogen through steam methane reforming (SMR) of natural gas and the gasification of eucalyptus biomass under Brazilian conditions. This study evaluated the environmental impacts of producing 1 kg of hydrogen in three scenarios: i) SMR - steam methane reforming of natural gas, ii) SMR-CCS - SMR with integrated carbon capture and storage, and iii) Gasification-WGS - eucalyptus gasification and the water-gas shift reaction. Using ReCiPe's midpoint (H) method, nine impact categories were selected through normalization, focusing on the most significant environmental impacts. The global warming (GW) category was identified as the most critical based on normalization results, which were further confirmed by endpoint normalization. The results show that the SMR and SMR-CCS scenarios generate 10.1 kg and 6.53 kg of CO_2 equivalent emissions, respectively. In contrast, the Gasification-WGS scenario emits only 1.23 kg of CO_2 equivalent (CO_2 eq./H_2), representing a reduction of approximately 87% compared to the SMR scenario. Although the SMR-CCS scenario results in a lower GW compared to SMR, it produces higher impacts in other environmental categories. Furthermore, the Gasification-WGS scenario shows a higher impact on eutrophication, particularly due to nutrient runoff from the cultivation and processing of eucalyptus biomass.

Keywords: Energy Transition. Sustainable Energy. Bio-based Hydrogen. CO_2 capture and storage. Biomass Utilization.

RESUMO

Uma avaliação do ciclo de vida (ACV) foi aplicada para comparar a produção de hidrogênio por reforma a vapor do metano (SMR) a partir do gás natural e pela gaseificação da biomassa de eucalipto em condições brasileiras. Este estudo avaliou os impactos ambientais da produção de 1 kg de hidrogênio em três cenários: i) SMR – reforma a vapor do metano a partir do gás natural, ii) SMR-CCS – SMR com captura e armazenamento de carbono integrado, e iii) Gaseificação-WGS – gaseificação de eucalipto e reação de deslocamento gás-água. Utilizando o método de nível médio (H) do ReCiPe, nove categorias de impacto foram selecionadas por meio da normalização, com foco nos impactos ambientais mais significativos. A categoria de aquecimento global (GW) foi identificada como a mais crítica com base nos resultados da normalização, sendo essa conclusão confirmada pela normalização de endpoint. Os resultados mostram que os cenários SMR e SMR-CCS geram, respectivamente, 10,1 kg e 6,53 kg de emissões de CO_2 equivalente. Em contraste, o cenário Gaseificação-WGS emite apenas 1,23 kg de CO_2 equivalente (CO_2 eq./H_2), representando uma redução de aproximadamente 87% em relação ao cenário SMR. Embora o cenário SMR-CCS apresente menor impacto na categoria de aquecimento global em comparação ao SMR, ele resulta em impactos mais elevados em outras categorias ambientais. Além disso, o cenário Gaseificação-WGS demonstra um impacto maior na eutrofização, principalmente devido ao escoamento de nutrientes provenientes do cultivo e processamento da biomassa de eucalipto.

***Palavras-chave*:** Transição Energética. Energia Sustentável. Hidrogênio de Base Biológica. Captura e Armazenamento de CO_2. Aproveitamento de Biomassa.

1. INTRODUCTION

E Energy resources have always been closely linked to human progress. In the 19th century, coal powered the industrial revolution. In the 20th century, oil and its derivatives dominated, driving the growth of the automotive and petrochemical industries. The extensive use of natural resources revealed the finite nature of energy reserves, leading to environmental policies focused on global warming aimed at creating alternatives to reduce greenhouse gas emissions through sustainable energy sources capable of meeting the world's growing energy demand (DA SILVA et al., 2021).

In Brazil, most hydrogen production comes from natural gas steam reforming, primarily consumed in refineries and fertilizer factories, with local production and use. The search for low-carbon hydrogen production alternatives as an energy vector is gaining attention due to its potential to replace fossil fuels and drive decarbonization. Petrobras' Strategic Plan for 2024-2028 foresees an investment of over US$ 102 billion aimed at expanding the supply and access to low-carbon energy and products, facilitating a profitable transition to reduce energy shortages and the portfolio's exposure to greenhouse gas emissions (PETRÓLEO BRASILEIRO S.A. — PETROBRAS, 2023).

Hydrogen is the most abundant element in the universe but is rarely found in its pure form on Earth. To obtain pure hydrogen, it must be extracted from hydrogen-containing compounds, a process that requires significant energy input. Hydrogen production is generally classified into three categories green, blue, and gray based on its environmental impact. This classification primarily depends on the energy sources and technologies employed in the production process. Grey hydrogen is primarily produced via Steam Methane Reforming (SMR) of natural gas, a process that is associated with substantial environmental impacts due to high carbon emissions throughout its production and application stages. In contrast, blue hydrogen also derived from fossil fuels incorporates Carbon Capture and Sequestration (CCS) technologies, which significantly reduces the carbon emissions otherwise released into the atmosphere (BORETTI, 2021).

Natural gas, consisting of 75-99% methane (CH_4), also includes heavier hydrocarbons and trace impurities and is stored in abundant reserves worldwide. Methane serves as a critical feedstock in various chemical engineering processes to produce synthesis gas (syngas), a mixture of carbon monoxide (CO) and hydrogen (H_2). Syngas is utilized across numerous downstream applications, including methanol synthesis, ethanol production, Fischer-Tropsch oil synthesis, hydroformylation, ammonia synthesis, and gasoline production (COWNDEN; MULLEN; LUCQUIAUD, 2023).

Currently, various technologies for Carbon Capture and Storage (CCS) are available at thermal power plants, involving CO_2 absorption through aqueous solutions containing different types of amines: primary, secondary, and tertiary, such as monoethanolamine (MEA), diglycolamine (DGA), 2-amino-2-methyl-1-propanol (AMP), diethanolamine (DEA), diisopropanolamine (DIPA), N-methylethanolamine (MMEA), methyl diethanolamine (MDEA), and triethanolamine (TEA) (YAN et al., 2020).

Amines are used in cyclic CO_2 capture processes involving two towers: one dedicated to absorption, where CO_2 reacts with primary or secondary amines to form carbamates, and a second for desorption, where heating releases CO_2 and regenerates the amine solution. This destruction, however, leads to higher energy demands and can increase corrosion within the system. The captured CO_2 is then compressed to pressures of 10–20 MPa and transported either over long distances by ships or, more commonly, through pipelines. Pipelines offer greater safety due to CO_2's non-toxic, non-flammable properties and its low leakage risk. Among storage options, underground geological storage is the most established, involving injection into suitable geological formations at controlled depths, which effectively isolates CO_2 and prevents its release back into the atmosphere (DZIEJARSKI; KRZYŻYŃSKA; ANDERSSON, 2023).

Green hydrogen is widely regarded as a clean energy source due to its production process, which relies on renewable energy, thereby minimizing its carbon footprint. It is primarily generated through water electrolysis, using electricity derived from renewable sources such as wind, solar, or hydropower. Another promising method of hydrogen production is biomass gasification, which holds significant potential in Brazil. The country’s vast agricultural and forestry biomass resources, including sugarcane bagasse, planted forests, and agricultural residues, make it an ideal candidate for this technology (NONATO et al., 2020).

These production methods contribute significantly to advancing renewable energy goals and improving energy security by reducing reliance on fossil fuels. Moreover, they align with global climate strategies by partially offsetting the CO_2 emissions from hydrogen production through the carbon absorbed during the biomass feedstock's growth phase. While not entirely carbon-neutral, this balance lowers the net carbon footprint compared to conventional hydrogen production methods. This dual advantage underscores green hydrogen's pivotal role in the transition to a sustainable energy future, combining environmental benefits with enhanced energy independence.

Biomass gasification can produce green hydrogen by thermochemically converting organic biomass into a hydrogen-rich gas mixture. In this process, biomass is heated to high temperatures (typically 700–1,500°C) in a low-oxygen environment, which prevents complete combustion and leads to the formation of syngas, primarily composed of H_2, CO and CO_2. To enhance hydrogen yield, the carbon monoxide in the syngas reacts with steam in a water-gas shift reaction, producing additional hydrogen and converting CO into CO_2. The integration of CCS technologies can further sequester CO_2, potentially resulting in a carbon-negative process. Finally, the hydrogen gas is separated and purified for use.

Hydrogen production through biomass gasification has gained attention as a viable alternative to conventional methods due to the efficiency of dual fluidized bed (DFB) systems combined with CO_2 adsorption. Using DFB systems and optimized catalysts, hydrogen yields can reach up to 70 vol% directly in the gasifier, making it highly competitive with natural gas reforming on a large scale. Advancements in process simulations have also demonstrated that biomass-based hydrogen production is economically feasible, especially when integrated into industrial applications such as refineries (RAUCH; HRBEK; HOFBAUER, 2014).

However, impurities in biomass syngas such as tar, ammonia (NH_3), hydrogen sulfide (H_2S), hydrogen chloride (HCl), hydrogen cyanide (HCN), sulfur dioxide (SO_2), and alkali metals—can pose significant challenges for downstream applications. Effective removal or reduction of these contaminants is essential and can be achieved through methods like cyclones, filters, electrostatic precipitators, and multifunctional processing techniques FRILUND et al., (2021); BRITO et al., (2023). Innovations in syngas cleaning technologies have focused on achieving high purity levels to improve syngas' quality and usability in hydrogen production. Primary methods like torrefaction, water washing, and alkali impregnation reduce tar and impurities during gasification, while secondary approaches like catalytic and thermal reforming further clean syngas by targeting contaminants. Techniques combining wet and dry methods, such as the OLGA system, have proven effective but are often costly due to complex filtering and catalyst requirements. Alternatives like non-thermal plasma and biochar catalysis offer cost-effective improvements and lower energy use, supporting more sustainable syngas production. Recent advances include integrated gasification and supercritical water gasification (SCWG), which reduce tar formation and improve efficiency for high-moisture biomass, enhancing economic feasibility and environmental impact (REY et al., 2024).

LCA studies are widely used to evaluate the environmental impacts of hydrogen production across its lifecycle. Hermesmann and Müller, (2022) conducted a comparative study on various hydrogen technologies (grey, blue, turquoise, and green) by applying LCA metrics. Their findings highlighted that environmental impacts vary significantly depending on the electricity and natural gas supply chains involved. This approach reveals the critical role of energy sources in determining hydrogen's overall environmental footprint and informs sustainable production practices in the hydrogen industry.

García et al., (2017) examine the environmental impact of producing hydrogen from Pinus patula biomass in Colombia through gasification, using a cradle-to-gate LCA. The study highlights that seedling production and forest cultivation are significant contributors to environmental impact, primarily due to agrochemical use and material demands in the seedling stage, and fertilizer application and diesel consumption during wood harvesting and transport.

In their study, Cho, Strezov and Evans, (2022), evaluate the environmental impacts of hydrogen production using SMR. By applying an LCA approach, they identify key contributors to greenhouse gas emissions and analyze potential reduction strategies, including increased production efficiency and alternative, renewable feedstocks.

Khojasteh Salkuyeh, Saville and MacLean, (2017) examined fossil fuel consumption and CO_2 emissions in hydrogen production technologies. The study found that the GWP of SMR is 11.7 kg CO_2 equivalent per kg of hydrogen without carbon capture and 3.5 kg with it. In contrast, the chemical looping reforming (CLR) process demonstrated a significantly lower GWP of 0.5 kg CO_2 equivalent when carbon capture is employed, making it only 14% of the GWP associated with carbon-capturing SMR. The CLR process also achieves life cycle greenhouse gas emissions that are 16%–26% lower than other technologies.

This study represents a novel analysis of potential environmental impacts associated with hydrogen production technologies in Brazil, focusing on natural gas reforming and eucalyptus gasification. By employing the life cycle assessment methodology, this research aims to provide valuable insights into the sustainability of these hydrogen production options within the Brazilian context, paving the way for informed decision-making and future advancements in clean energy technologies.

2. METHODOLOGY

The study applies the Life Cycle Assessment (LCA) methodology, utilizing SimaPro 9.5.0.0® software, developed by PRé Sustainability (1990 - 2023), for inventory compilation and impact calculations. The analysis adheres to the phases prescribed by the ABNT NBR ISO 14040 standards, ensuring compliance with internationally recognized guidelines for conducting LCAs.

2.1. Definition of goal and scope

This study aims to analyze and compare the environmental impacts of different hydrogen production technologies in Brazil, focusing on three specific scenarios: steam methane reforming of natural gas: SMR, SMR of natural gas with integrated carbon capture and storage: SMR-CCS and green hydrogen production via eucalyptus gasification and the water-gas shift reaction: Gasification-WGS.

The study defines the Functional Unit (FU) as the production of 1 kg of hydrogen. All contributions from the process and environmental impacts are assessed relative to this functional unit of hydrogen production. A comparison with fossil hydrogen (SMR and SMR-CCS) is also made using the same functional unit of 1 kg of green hydrogen produced from eucalyptus gasification and the water-gas shift reaction (Gasification-WGS).

The LCA adopts a cradle-to-factory-gate approach, beginning with the extraction of raw materials and their transportation to the hydrogen production site. The study excludes post-production phases, such as hydrogen consumption, and infrastructure processes related to transportation, storage, and distribution. Additionally, long-term emissions are not considered within the study's boundaries.

The geographical scope of this study encompasses a hydrogen production plant situated in the state of Minas Gerais, Brazil. For the fossil hydrogen scenarios (SMR and SMR-CCS), the study considers onshore, high-pressure natural gas production originating in Bolivia. This gas is transported to Brazil via maritime shipping, covering an average distance of 7,100 km, and subsequently distributed through long-distance pipelines spanning 1,700 km. Within Brazil, natural gas is transported through pipelines with distances of approximately 3,000 km from Fortaleza to São Paulo and 300 km from the Santos Basin to São Paulo.

The forestry scenario utilized in this study is based on the inventory developed by SARA et al., (2016), which details eucalyptus cultivation over a 14-year cycle in Minas Gerais. The analysis encompasses all inputs and outputs associated with the production process, starting from the initial stage of seedling production. Fuel consumption by machinery used in agroforestry management was accounted for throughout the entire production cycle. Additionally, the production and transportation of seedlings, as well as the use of agrochemicals including herbicides, insecticides, and fungicides were included within the system boundaries to ensure a comprehensive assessment.

The temporal scope is set at 30 years, aligning with the life cycle of hydrogen production in the three evaluated scenarios (SMR, SMR-CCS, and Gasification-WGS). This timeframe reflects the operational lifespan of natural gas extraction infrastructure, CCS, and the eucalyptus plantations used in biomass gasification for green hydrogen production (TAVARES BORGES et al., 2024).

Figures 1 and 2 illustrate the system boundaries for the SMR/SMR-CCS and Gasification-WGS technologies, respectively, clarifying the scope of analysis for each scenario.

The study employs the ReCiPe Endpoint (H) method in Life Cycle Impact Assessment (LCIA), a systematic approach that translates emissions and resource extraction into a limited set of environmental impact scores using characterization factors. This approach also aggregates the midpoint indicators into three overarching damage categories: human health, ecosystem quality, and resource availability. The endpoint methodology simplifies comparisons by presenting a holistic view of the environmental trade-offs associated with each scenario. This combined application of midpoint and endpoint methods enables a robust comparison of the environmental performance of the hydrogen production scenarios, offering both detailed insights and an overarching assessment of their sustainability (HUIJBREGTS et al., 2017).

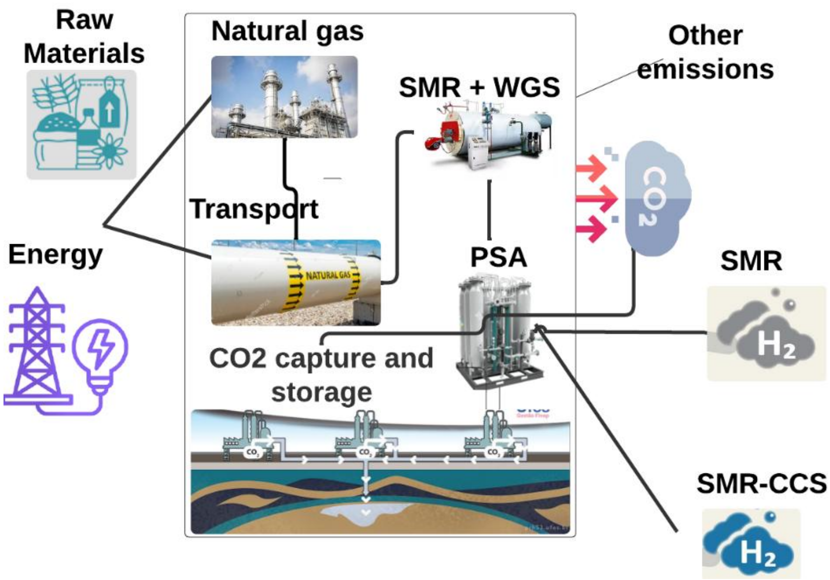

Figure 1: System boundaries for the SMR and SMR-CCS technologies.

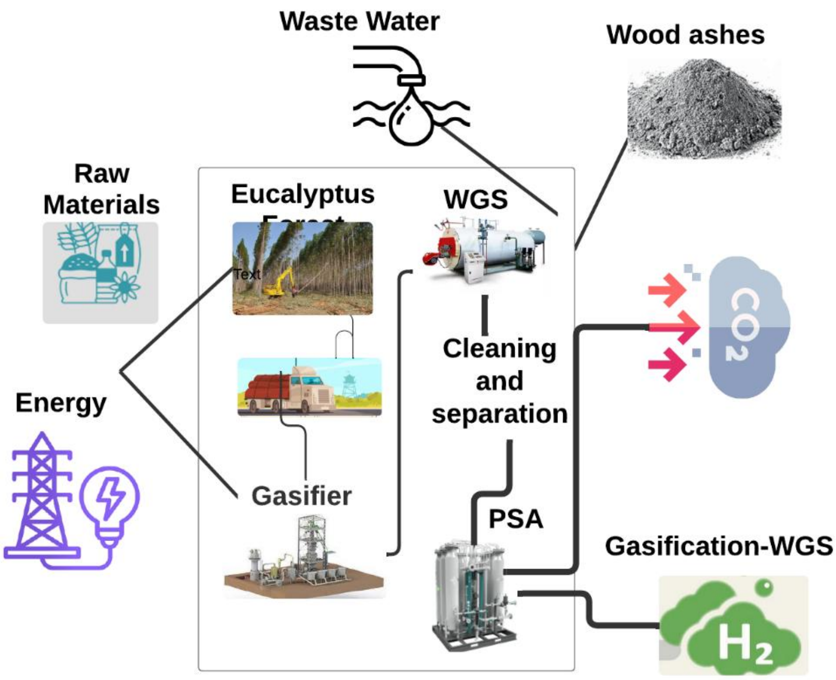

Figure 2: System boundaries for the Gasification-WGS technologies.

In conducting the LCIA, models and indicators are applied to evaluate the impacts of various inputs and outputs across selected impact categories. To determine which categories are most relevant, this study adopts the methodology outlined by WEIDNER; TULUS; GUILLÉN-GOSÁLBEZ, (2023), which incorporates normalization as a critical step for selecting the most relevant impact categories. Normalization involves scaling results against a reference value, such as the global average impact for each category, enabling a comparative perspective that highlights the most critical environmental concerns. This systematic process ensures a focused analysis on categories with the greatest environmental relevance, improving the clarity and applicability of the findings.

Based on the normalization results presented in Section 3, nine impact categories were identified as having the highest environmental relevance for the life cycles evaluated in this study. These categories include Global Warming (GW), Ozone Formation, Human Health (OFHH), Fine Particulate Matter Formation (FPMF), Freshwater Eutrophication (FE), Terrestrial Ecotoxicity (Tec), Marine Ecotoxicity (Mec), Human Carcinogenic Toxicity (HCT), Fossil Resource Scarcity (FRS), and Water Consumption (WC).

2.2. Life cycle inventory (LCI)

The LCI data for this study draws on diverse sources, offering comprehensive details on inputs (raw materials, energy, water) and outputs (atmospheric emissions, liquid effluents, solid waste) critical for assessing environmental impacts related to hydrogen production scenarios. This data was integrated into the SimaPro software for efficient analysis. Specific inputs include natural gas data from Capaz et al. (2020), eucalyptus production data from Alves et al. (2024), with scenarios SMR and Gasification-WGS informed by HREN et al., (2023) and SMR-CCS supported by DUVAL-DACHARY et al., (2023). Together, these sources provide a robust foundation for evaluating the environmental impacts of hydrogen production pathways in Brazil. Further details will be explored in the sections that follow.

2.2.1. Steam methane reforming of natural gas (SMR)

In methane steam reforming for hydrogen production, natural gas undergoes desulfurization in a pre-treatment stage to remove sulfur compounds, which can deactivate catalysts in later steps. During this desulfurization process, a portion of the hydrogen produced is recycled back to aid in the hydrogenation of carbonyl sulfide, a sulfur compound. This hydrogenation process converts carbonyl sulfide to hydrogen sulfide, facilitating more efficient sulfur removal and protecting downstream equipment.

The treated natural gas then reacts with superheated steam provided by a cogeneration unit, initiating the reforming process to generate a hydrogen-rich synthesis gas. This syngas undergoes partial carbon monoxide conversion in the water-gas shift section, where CO is reacted with water to yield additional hydrogen and CO_2. Crude hydrogen is then purified through pressure swing adsorption (PSA), yielding 99.95% pure hydrogen. During PSA, impurities are burned with air and natural gas, releasing CO_2 directly into the atmosphere (CETINKAYA; DINCER; NATERER, 2012).

In 2021, Brazil's natural gas consumption reached approximately 1,400 billion cubic feet (Bcf), with domestic production at around 839 Bcf. Although natural gas represented about 7% of Brazil's total energy production that year, the country remains a net importer, primarily sourcing gaseous natural gas from Bolivia (25%) and, increasingly, liquefied natural gas (LNG) to meet rising demand. From 2012 to 2022, LNG imports grew at an average annual rate of 75%, with most imports in 2022 coming from the United States (76%) and Qatar (14%), via regasification terminals (IEA, 2022). Expanding domestic infrastructure and implementing market reforms are helping to drive Brazil’s natural gas and LNG market, but challenges remain, including the long distances from offshore fields and limited pipeline infrastructure connecting gas fields to the coast (“Brazil - Countries & Regions - IEA”, 2024).

The Life Cycle Inventory (LCI) data for producing 1 kg of gray hydrogen were compiled using a combination of experimental data and database resources. Input and output data specific to natural gas production, adapted to Brazilian conditions, were based on experimental findings from (CAPAZ et al., 2020), as detailed in Table 1. Baseline data for other materials and energy inputs were sourced from the Ecoinvent 3 database within the SimaPro software, as outlined in the supplementary material. This comprehensive approach ensured a robust LCI for evaluating the environmental impacts associated with gray hydrogen production.

Table 1: LCI for 1 m³ of natural gas in Brazil (Source: Adapted from Capaz et al., 2020)

Inputs	Quantity	Unit
liquefied natural gas (LNG)	9,50E-02	m^3
Domestic Onshore Production	1,34E-01	m^3
Domestic Offshore Production	3,93E-01	m^3
international onshore production	3,71E-01	m^3
LNG transport	4,98E-01	tkm
Transport Of Imported LNG (Onshore)	4,67E-01	tkm
Domestic Land Transport	5,45E-01	tkm
Domestic Land Transport (Repeated)	5,45E-01	tkm
Offshore Transport	1,62E-01	tkm

Tables 2 and 3 detail the LCI data for producing 1 kg of gray hydrogen, using information adapted from Hren et al. (2023). This inventory includes essential inputs, such as natural gas and other raw materials, as well as energy usage, and outputs, including atmospheric emissions, across each stage of the hydrogen production process. By following the LCA methodology, this approach enables a systematic analysis of environmental impacts and resource requirements associated with the steam reforming process. Data collection focused on critical resources and emissions, capturing the environmental footprint from initial natural gas consumption to final hydrogen output, and providing an in-depth characterization of the production process's environmental impacts.

Table 2: LCI data to produce 1 kg of SMR. (Source: Adapted from HREN et al., 2023)

Inputs	Quantity	Unit
Natural gas	4,74E+00	m^3
Steam	1,00E+01	kg
Electricity	1,14E+00	MJ
Water	1,89E-02	m^3

Table 3: Emissions to air during the production of 1 kg of grey hydrogen (Source: Adapted from Hren et al., 2023)

Output	Quantity	Unit
CO_2	4,9E+00	kg
CH_4	4,74E-03	kg
Waste, solid	2,02E-01	kg

2.2.2. Steam methane reforming of natural gas with integrated carbon capture and storage (SMR-CCS)

Blue hydrogen technology builds upon the processes used in gray hydrogen production by integrating CCS to reduce GHG emissions. This approach involves capturing the CO_2 generated during hydrogen production and sequestering it in deep geological formations, such as depleted oil and gas reservoirs or saline aquifers.

In this study, CO_2 capture occurs during the pre-combustion stage using an amine-based absorption method, with monoethanolamine (MEA) serving as the chosen solvent. MEA efficiently captures CO_2 from high-pressure gas streams generated during the pressure swing adsorption (PSA) stage of hydrogen purification. Leveraging MEA's high chemical affinity for CO_2, this process effectively separates CO_2 (XUE et al., 2023)).

The selection of MEA was based on its proven efficiency and versatility in treating high-pressure gas streams, attributes that make it ideal for CO_2 capture in hydrogen production applications. MEA is widely utilized in carbon capture due to its ability to handle significant volumes of gas under high-pressure conditions. Additionally, MEA's cost-effectiveness, ease of regeneration, and well-documented research support its viability as a balanced choice for amine-based CO_2 capture, promoting both operational efficiency and economic feasibility in large-scale hydrogen production (DUVAL-DACHARY et al., 2023).

The CO_2 in the flue gas reacts with MEA to form a weakly bonded compound. The CO_2 and MEA-rich solution then flows into a secondary reactor, where it is heated to break these weak bonds, releasing CO_2 and regenerating the MEA solvent. This regeneration step, though efficient, requires a substantial energy input. Once separated, the CO_2 stream, now nearly pure, is directed for compression and transport. Table 4 provides detailed inventory data for each step of the CO_2 capture and handling process, illustrating the inputs and outputs associated with this method.

Before re-entering the primary reactor, the MEA solution undergoes a purification step to remove stable salts that form due to interactions with acidic gases (such as SO_2, SO_3, NO_2, and *HCl*) present in the flue gas. This purification process typically uses activated carbon to filter out these salts, with additional MEA recovered through the addition of sodium hydroxide. However, MEA also degrades over time due to oxidation from the combustion gas's oxygen content and the heat generated during solvent regeneration. This degradation results in emissions, including NH_3 and other byproducts, which can either be released to the atmosphere or washed out by a water-washing system to mitigate atmospheric emissions.

Table 4: Inventory data for the capture of 4,4 kg of CO_2 eq/kg H_2 produced (DUVAL-DACHARY et al., 2023).

Inputs	Quantity	Unit
NaOH	6,37E-04	kg
Activated carbon	3,68E-04	kg
Solvent (MEA)	1,00E-02	kg
Water	3,09E-03	t
Heating	1,81E-02	GJ
Cooling (Water)	5,07E-01	t
Electricity (Pumping)	1,47E-04	MWh
Electricity (Compression)	3,43E-04	MWh

The carbon capture process in this study includes electricity consumption associated with both the capture and transportation of CO_2. The capture technology employed demonstrates an efficiency of 89.8%. The leakage rates are further detailed in Table 5, which outlines the emissions related to the carbon capture process and evaluates the performance metrics of the technology used.

Table 5: Main atmospheric emissions during the capture of 4,4 kg of CO_2 eq/kg H_2 produced (DUVAL-DACHARY et al., 2023)

Output	Quantity	Unit
Ammonia	1,40E+00	g
MEA	2,00E-01	g
CO_2	5,00E-01	kg

The inventory data for transportation of H_2 were adapted using a datasetfor long-distance natural gas pipelines from Brazil to importing countries, available in the SimaPro Ecoinvent 3 database (WERNET et al., 2016). This data set describes the energy consumption and emissions associated with transport from the production site to export via a long-distance pipeline.

The transportation of CO_2 over long distances through pipelines relies on compressor stations fueled by natural gas. The system capacity is estimated at 14,010 tonnes of CO_2, covering a transport distance of 300 km. For the compression process during transport, an energy demand of 0.0171 kWh per kg of CO_2 is applied, based on the results of HERMESMANN; MÜLLER, (2022). Calculations are based on factors like pipeline length, CO_2 flow rate, and pressure losses across compressor stations. Compressor stations, often powered by natural gas, add a significant energy requirement, influencing both the operational efficiency and environmental footprint of CO_2 transport systems.

Inventory data used to estimate the primary inputs and emissions associated with transporting and storing 4.4 kg of CO_2 was adapted from DUVAL-DACHARY et al., (2023), as detailed in Table 6. This information provides insights into the resources consumed and emissions produced during CO_2 transport and storage.

Table 6: Inventory data for transport and Storage of 4.4 kg of CO_2 per kg of hydrogen produced (Adapted from DUVAL-DACHARY et al., 2023)

Inputs	Quantity	Unit
Electricity *	4,89E-01	kWh
Compress*	7,50E-05	kWh
Production Volume*	1,53E-03	kg.km
Electricity **	3,08E-02	kWh

*Transporting Captured CO_2 ** Storage of Captured CO_2

The CO_2 leakage rate during transport and subsoil injection is 0.07% of the total CO_2 captured, translating to approximately 0,00031 kg of CO_2 leakage per kg of hydrogen produced. This rate accounts for the minor emissions that occur in the stages of CO_2 transportation and geological storage (DUVAL-DACHARY et al., 2023).

2.2.3. Green hydrogen from eucalyptus gasification and water-gas shift reactions (Gasification-WGS)

This scenario begins with the production of eucalyptus seedlings, where key inputs and outputs necessary to cultivate 16.3 kg of eucalyptus biomass required to yield 1 kg of hydrogen, were cataloged and calculated (SALKUYEH; SAVILLE; MACLEAN, 2018). These calculations draw on the eucalyptus LCI data outlined by and include both material and energy inputs, as well as emissions and other outputs generated during the forest production stage.

The hydrogen production process via eucalyptus gasification in this study assumes a transportation distance of 100 km to the production unit. The process is divided into four key stages, as outlined in the methodology of KARGBO; NG; PHAN, (2022), and illustrated in Figure 3. These stages encompass the complete lifecycle from eucalyptus cultivation to its conversion into hydrogen.

Stage 1: Feed preparation: The eucalyptus, with an initial moisture content of 30%, undergoes cutting and fragmentation before passing through a hammer crusher that reduces its particle size to approximately 1 cm. This material then enters a rotary dryer, which decreases the moisture content to 10% by weight. During drying, the air exiting the rotary dryer is directed through a cyclone and a bag filter to capture any particulate matter.

Stage 2: Gasification-water gas shift (WGS): The dried eucalyptus is introduced into a gasifier, where it is heated to high temperatures, typically between 700°C and 1,000°C, in the presence of a gasifying agent. In this study, water vapor (H_2O) is used alongside air to facilitate the gasification process. Olivine, a mineral commonly used in this type of gasification, plays a crucial role by regulating the reactions, enhancing the production of synthesis gas, and neutralizing acids like CO_2. Additionally, olivine aids in heat transfer, thus improving the overall efficiency of the process.

After gasification, the resulting raw synthesis gas contains impurities such as tar, which must be removed to ensure the efficiency and longevity of downstream equipment. To achieve this, the gas is directed to a tar reformer, where the tar undergoes thermal cracking, breaking it down into hydrogen and carbon monoxide. This critical step removes tar and other unwanted compounds that could damage catalysts and interfere with subsequent gas cleaning systems. Following tar removal, the cleaned gas enters the Water-Gas Shift (WGS) reactor, where further chemical reactions occur to convert carbon monoxide into carbon dioxide, producing additional hydrogen in the process.

Stage 3: Cleaning and separation: The synthesis gas generated in step 2 still contains impurities such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), ammonia (NH_3), alkali metals and tar. To ensure the proper gas purity, these impurities are removed by a multi-stage purification process. The use of amine scrubbers and liquid oxidation is combined with filtration through a bed of zinc oxide (ZnO), which removes sulfur compounds such as H_2S. In addition, ethylene glycol is used in the process to capture moisture and other volatile contaminants, contributing to the removal of additional impurities and improving purification efficiency.

The process also involves cooling the hot gases to 150°C through heat exchange with heat recovery devices, increasing the efficiency of the overall process. The water extracted from the washing process is directed to appropriate treatment in external facilities. Before the synthesis gas enters the PSA stage, it is important to eliminate any residual moisture to protect the adsorbents used in the hydrogen separation, which is done by additional cooling to reduce the temperature to 43°C.

Stage 4: Hydrogen Separation and Purification**:** Before being released from the system, hydrogen is purified by a Pressure Swing Adsorption (PSA) unit, which removes CO_2 and produces high-purity hydrogen. The resulting residual gas undergoes an additional two-stage separation process using polymeric membranes, aimed at capturing CO_2 and reducing the greenhouse gas (GHG) footprint. This process not only ensures high-quality hydrogen but also helps mitigate emissions associated with gas production, aligning with sustainable decarbonization practices.

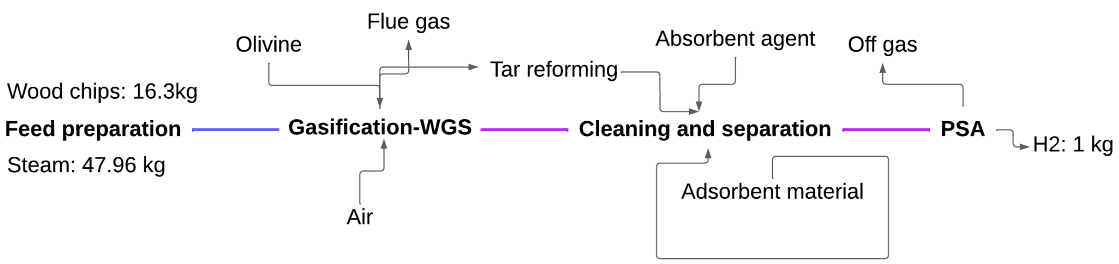

Figure 3. Eucalyptus Gasification-WGS for hydrogen production

The inventory calculations and primary emissions detailed in Tables 7 and 8 were derived using the methodology established by HREN et al., (2023). This approach systematically evaluates the various inputs and outputs throughout the hydrogen production process, including emissions associated with each stage. By following their methodology, a comprehensive analysis of the environmental impacts and resource utilization can be achieved, providing a clearer understanding of the overall carbon footprint of hydrogen production.

Table 7: Inventory data to produce 1kg of green hydrogen **(**HREN et al., (2023)

Inputs	Flow Source	Quantity	Unit
Eucalyptus Wood	Technosphere	2,26E-02	m^3
Steam	Technosphere	2,54E+00	Kg
Olivine	Nature	5,48E-01	Kg
Air	Nature	1,68E+02	Kg
Ethylene Glycol	Technosphere	2,00E-03	Kg
Zinc Oxide	Technosphere	6,00E-03	Kg
Electricity	Technosphere	1,29	MJ

Table 8: Main Emissions to produce 1 kg of Green Hydrogen (Source: Adapted from .

Output	Sink	Quantity	Unit
Biogenic CO_2	Air	1,19E+01	kg
Ethylene Glycol	Air	2,00E-03	kg
Zinc Oxide	Air	6,00E-03	kg
Waste water	Water	1,94E+01	kg
Wood ashes	Final waste flows	3,50E-01	kg

3. RESULTS AND DISCUSSION

This section will first analyze the scenarios based on fossil fuels separately from the renewable-based scenario to provide a specific understanding of their contributions to environmental impacts. By examining each scenario in isolation, we can identify the strengths and weaknesses inherent in fossil fuel versus renewable hydrogen production methods. Following this detailed analysis, a comparative evaluation will be conducted to contrast the overall performance of these options.

3.1. Contribution analysis of SMR and SMR-CCS

The characterized results for SMR are presented in Figure 4 and Table 9, which provide the midpoint results to produce 1 kg of gray hydrogen. Each environmental category was evaluated to assess its contribution, highlighting effects of hydrogen production from natural gas.

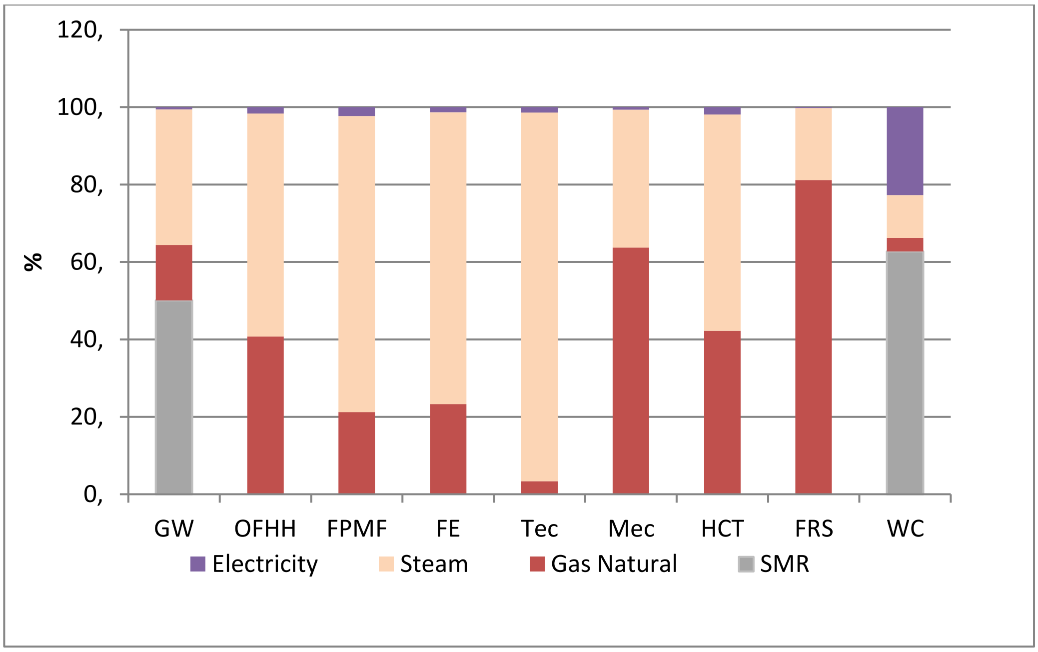

Figure 4: LCIA of producing 1 kg of SMR technology: Characterization

Table 9: Environmental Impact Characterization of 1 kg of SMR

IC	Unit	SMR	Natural Gas	Steam	Electricity	Total
GW	Kg CO_2 eq.	5,07E+00	1,45E+00	3,55E+00	5,40E-02	1,01E+01
OFHH	Kg Nox eq.	0,00E+00	3,54E-03	5,00E-03	1,38E-04	8,68E-03
FPMF	Kg PM2,5 eq.	0,00E+00	8,74E-04	3,14E-03	9,56E-05	4,11E-03

FE	Kg P eq.	0,00E+00	1,57E-05	5,10E-05	8,82E-07	6,76E-05
Tec	Kg 1,4-DCB	0,00E+00	4,20E-01	1,19E+01	1,70E-01	1,25E+01
Mec	Kg 1,4-DCB	0,00E+00	1,35E-02	7,54E-03	1,35E-04	2,12E-02
HCT	Kg 1,4-DCB	0,00E+00	8,94E-03	1,18E-02	3,95E-04	2,12E-02
FRS	Kg oil eq	0,00E+00	4,30E+00	9,85E-01	1,10E-02	5,29E+00
WC	m^3	1,89E-02	1,04E-03	3,34E-03	6,85E-03	3,01E-02

SMR has significant environmental impacts, particularly in the categories of global warming (GW) and water consumption (WC). For GW, SMR contributes approximately 50% of the total indicator results, largely due to direct emissions from methane combustion and reforming processes. Steam production accounts for an additional 35%, driven by its high energy intensity, often supplied by natural gas-powered systems. The natural gas life cycle itself contributes about 14% to the total GW impact, stemming from extraction, processing, and transportation activities. This is consistent with findings by (ONI et al., (2022), who also highlighted the substantial carbon footprint of SMR due to its reliance on fossil fuels for both steam production and hydrogen extraction.

The impact on the Water Consumption (WC) category in the SMR system is primarily driven by the steam methane reforming (SMR) process itself, which accounts for 62% of the total impact. This reflects the intensive use of water directly in the chemical reactions and cooling operations associated with the process. Electricity generation contributes 22%, due to the water demands associated with power generation in Brazil’s energy matrix, which is predominantly thermoelectric and hydroelectric. Industrial steam generation adds 11%, as external systems are required to meet the steam demands of the SMR process. Finally, natural gas consumption accounts for 3.4%, reflecting its use as both a feedstock and an energy source.

This breakdown clarifies that the water consumption attributed to steam production is considered as part of the broader SMR system, encompassing both internal operations and the external generation of steam. It underscores the importance of optimizing water usage across all stages to mitigate the environmental burdens associated with the process.

The intensive use of natural gas significantly impacts human carcinogenic toxicity (HCT), marine ecotoxicity (Mec), and fossil resource scarcity (FRS), with contributions ranging between 58% and 81%. These effects are primarily attributed to the fossil nature of natural gas, which releases heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other pollutants during combustion. It is important to note that the emissions from the combustion of natural gas are included in the natural gas life cycle inventory, which accounts for the entire process from extraction to use. These emissions are therefore not separately accounted for in the SMR process itself, but are attributed to the natural gas lifecycle, which impacts the HCT, MEC, and FRS categories.

In addition, the steam production step contributes substantially to ozone formation (OFHH), fine particle formation (FPMF), freshwater eutrophication (FE) and terrestrial ecotoxicity (Tec), with particle emissions accounting for between 58% and 95% of the impacts in these categories. These high levels of impact are attributed to the high demand for thermal energy and the combustion of natural gas throughout the SMR process, highlighting the need for emission control measures and cleaner technologies to reduce associated environmental damage.

The results of this study are consistent with existing literature on gray hydrogen production, with the calculated emissions falling within the range observed in previous assessments. Studies conducted by CHO; STREZOV; EVANS, (2022) and (BOROLE; GREIG, 2019) reported emission factors of 9.35 and 10.4 kg CO_2 eq/kg H_2, respectively. The value determined in this study, 10.1 kg CO_2 eq/kg H_2, aligns with these estimates.

Variations in reported emission factors across studies can be attributed to multiple factors, including differences in process efficiency, the composition of the natural gas feedstock, technological advancements, and methodological choices in life cycle assessments. Additionally, aspects such as reactor configurations, operational conditions, and the presence (or absence) of emission mitigation technologies can significantly influence the results.

The relative proximity of these values reinforces the reliability of the models used to estimate emissions from hydrogen production via steam methane reforming (SMR). However, standardizing methodologies remains crucial to improving comparability between studies and supporting informed decision-making in the transition to a low-carbon economy.

The characterized results of the Life Cycle Impact Assessment (LCIA) for the SMR-CCS scenario are presented in Figures 5 and Table 10. These results illustrate the percentage contribution of various environmental categories to the production of 1 kg of hydrogen.

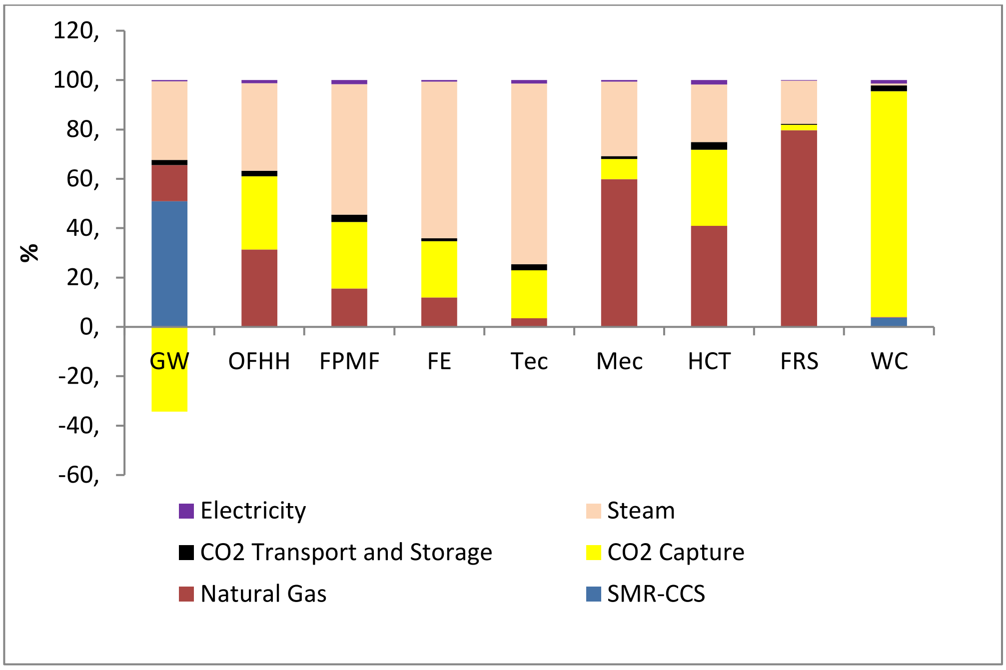

Figure 5: LCIA of producing 1 Kg of SMR-CCS technology: Characterization

SMR-CCS technology accounts for more than 50% of total emissions in the Global Warming (GW) category and approximately 2% in the Water Consumption (WC) category. Within this contribution, the largest share of emissions in GW stems from the SMR process steps, which are responsible for total emissions as follows:

- Natural gas use (14%), both as a feedstock and energy source, resulting in direct CO_2 emissions from combustion and process reactions.
- Steam production (31%), which requires significant energy input, often derived from fossil fuels, for high temperature generation.
- Electricity consumption (0.5%), which has a minor contribution due to the Brazilian electricity grid composition. The South-eastern/Mid-western grid is characterized by a mix of energy sources with a predominance of hydroelectric power, which has a lower carbon footprint compared to grids reliant on fossil fuels. However, emissions are still present due to the inclusion of thermoelectric sources and the life cycle impacts of infrastructure and energy transmission.

In addition to SMR emissions, the CO_2 transport and storage step contributes only 4% of total emissions, showcasing its relatively low environmental impact. Meanwhile, the CO_2 capture process significantly reduces emissions, contributing to an approximate 72% reduction in total greenhouse gas emissions, as it prevents a substantial portion of the CO_2 generated during the

SMR process from being released into the atmosphere.

The CO_2 capture stage generates significant emissions (over 43%) in the OFHH, FPMF, HCT, and WC categories. These high levels of impact are attributed to the energy-intensive processes involved in the capture and compression of CO_2, which demand significant amounts of thermal and electrical energy. While the CCS process effectively reduces greenhouse gas emissions by capturing CO_2 from the SMR, it introduces environmental impacts associated with its own energy requirements. This highlights the need for optimizing energy efficiency and incorporating cleaner energy sources to mitigate the environmental burdens of CCS operations

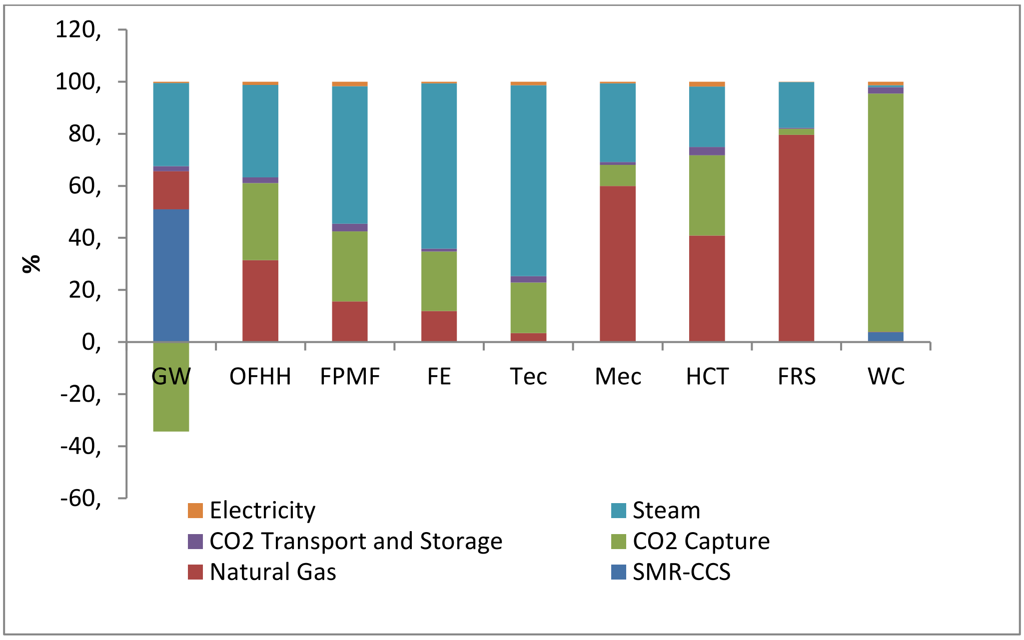

Table 10: LCIA of producing 1 Kg of SMR-CCS technology: Characterization

IC	Unit	SMR	Natural Gas	Steam	Electricity	CO2 Capture	CO2 Transport	Total
GW	Kg CO_2 eq.	5,07E+00	1,45E+00	3,17E+00	5,40E-02	-3,42E+00	2,04E-01	6,53E+00
OFHH	Kg Nox eq.	0,00E+00	3,54E-03	4,00E-03	1,38E-04	3,34E-03	2,41E-04	1,13E-02
FPMF	Kg PM2,5 eq.	0,00E+00	8,74E-04	2,96E-03	9,56E-05	1,51E-03	1,67E-04	5,60E-03
FE	Kg P eq.	0,00E+00	1,57E-05	8,40E-05	8,82E-07	3,02E-05	1,54E-06	1,32E-04
Tec	Kg 1,4-DCB	0,00E+00	4,20E-01	8,91E+00	1,70E-01	2,37E+00	2,97E-01	1,22E+01
Mec	Kg 1,4-DCB	0,00E+00	1,35E-02	6,82E-03	1,35E-04	1,84E-03	2,36E-04	2,25E-02
HCT	Kg 1,4-DCB	0,00E+00	8,94E-03	5,08E-03	3,95E-04	6,73E-03	6,90E-04	2,18E-02
FRS	Kg oil eq	0,00E+00	4,30E+00	9,48E-01	1,10E-02	1,21E-01	1,91E-02	5,40E+00
WC	m^3	1,89E-02	1,04E-03	3,84E-03	6,85E-03	4,58E-01	1,20E-02	5,01E-01

CO_2 capture significantly contributes to OFHH, FPMF, and HCT, releasing ozone precursors, fine particles, and carcinogenic chemicals. Steam production also plays a major role in FE, due to nutrient release, and in Tec, with toxic byproducts from the capture process. Natural gas extraction primarily drives the Mec and FRS, emitting chemicals that harm marine ecosystems and depleting fossil resources. Additionally, CO_2 capture is the dominant contributor to WC, reflecting the water intensity of the capture process. These results highlight the trade-offs in environmental impact across various categories, underscoring the need for optimization in steam generation and CO_2 capture technologies to mitigate negative effects.

3.2. Contribution analysis of Gasification-WGS

The characterized results are presented in Figure 6 and Table 11, illustrating the percentage contributions of various environmental categories associated with the production of 1 kg of hydrogen in Eucalyptus Gasification and Water-Gas Shift.

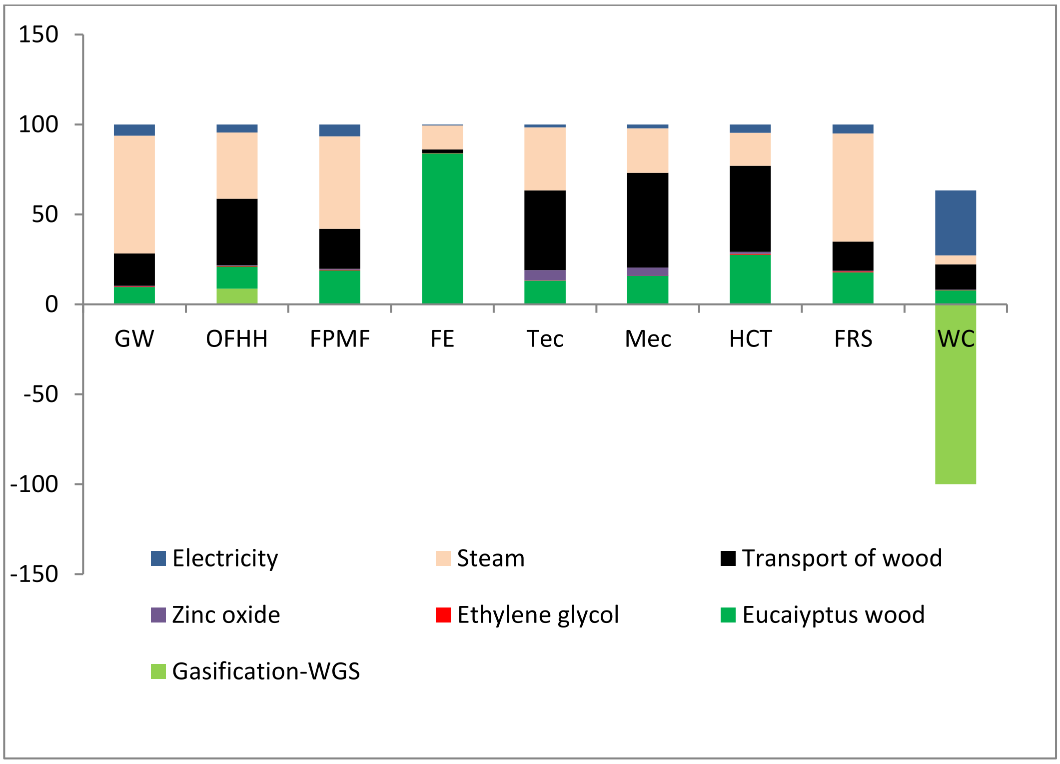

Figure 6: LCIA of producing 1 Kg of Eucalyptus Gasification and Water-Gas Shift technology: Characterization

The GW impact is primarily driven by steam stages, which account for nearly 65% of emissions. Specifically, the eucalyptus wood contributes 10% of emissions. The electricity is primarily (6%) consumed in the gasification process, including the operation of auxiliary systems such as compressors for gas separation and purification, and in the water-gas shift reaction (WGS) to optimize the hydrogen yield. These energy-intensive processes rely significantly on electricity to ensure the system operates under the required conditions for hydrogen production.

Additionally, eucalyptus transportation contributes approximately 18% to the GW impact, reflecting the emissions from fossil fuel use in transport vehicles. This highlights the importance of optimizing both energy efficiency and logistics to mitigate the environmental burdens associated with the process.

Table 11: LCIA of producing 1 Kg of Eucalyptus Gasification and Water-Gas Shift technology: Characterization

IC	Unit	Gasification and WGS	Eucalyptus wood	Ethylene glycol	ZnO	Transport	Steam	Eletrecity
GW	Kg CO2 eq.	0,00E+00	1,17E-01	4,22E-03	4,62E-03	2,20E-01	8,04E-01	7,74E-01
OFHH	Kg Nox eq.	2,40E-04	3,40E-04	8,66E-06	1,00E-05	1,03E-03	1,02E-03	1,23E-03
FPMF	Kg PM2,5 eq.	0,00E+00	2,77E-04	5,74E-06	6,41E-06	3,26E-04	7,52E-04	9,77E-04
FE	Kg P eq.	0,00E+00	1,34E-04	1,37E-07	1,37E-07	3,01E-06	2,13E-05	9,26E-06
Tec	Kg 1,4-DCB	3,86E-04	8,48E-01	1,14E-02	3,74E-01	2,85E+00	2,26E+00	1,06E+00
Mec	Kg 1,4-DCB	7,68E-08	1,11E-03	8,62E-06	3,15E-04	3,70E-03	1,73E-03	1,56E-03
HCT	Kg 1,4-DCB	0,00E+00	1,93E-03	4,24E-05	7,02E-05	3,36E-03	1,29E-03	3,20E-03
FRS	Kg oil eq	0,00E+00	7,12E-02	2,19E-03	1,35E-03	6,53E-02	2,40E-01	2,01E-01
WC	m3	-1,94E-02	1,51E-03	5,21E-05	1,87E-05	2,74E-03	9,74E-04	7,01E-02

In the OFHH category, the main contributors to ozone precursor emissions are transport of wood (37%) and steam (31.2%), followed by eucalyptus wood (12.3%) and electricity (4%). The intensive electricity generation and thermal energy consumption during the process lead to significant emissions, impacting human health (HCT). Additionally, emissions from eucalyptus transport also contribute to this impact.

The FPMF category exhibits higher emissions in eucalyptus gasification due to the high energy consumption for steam generation (51%), biomass transport (22%), and eucalyptus wood processing (19%). Steam production, essential for the gasification reactions, often requires thermal energy derived from fossil fuels, contributing to indirect emissions and promoting the formation of secondary particles. Biomass transport, primarily carried out by diesel-powered vehicles, releases particulate matter both from fuel combustion and from wear on tires and brakes. Additionally, biomass processing, including harvesting, shredding, and, in some cases, drying, involves heavy machinery that also runs on fossil fuels, further intensifying particle release. The combination of these factors explains the prominence of the FPMF category in the environmental impact of eucalyptus gasification, highlighting the need for strategies to reduce emissions, such as electrifying transport, using renewable sources for steam generation, and optimizing supply logistics.

The FE category shows that eucalyptus production is the primary driver of eutrophication, accounting for 90% of the impact. This is attributed to the use of fertilizers and pesticides that can lead to nutrients runoff into water bodies, promoting eutrophication. Steam also plays a significant role (13%), as its intensive use in the process can have indirect impacts on eutrophication through water and energy consumption. In Tec, eucalyptus transport (44%), steam (35%), and eucalyptus production (13%) are the leading contributors, highlighting that terrestrial ecotoxicity is closely linked to logistics, energy consumption, and the use of agrochemicals. The role of electricity generation is also important in processes involving toxic substances, contributing to the environmental impact in this category.

3.3. Comparative LCIA analysis of hydrogen production

The impacts of hydrogen production through steam reforming of natural gas (SMR and SMR-CCS) and gasification-WGS are evaluated for the functional unit of producing 1 kg of hydrogen, as illustrated in the normalized results in Figure 7. To focus on the most significant environmental impacts, we applied normalization using the World (2010) methodology. This method scales the impact categories to reflect their global significance, allowing for a clearer comparison between the production routes, specifically in terms of global warming potential, resource depletion, and air quality.

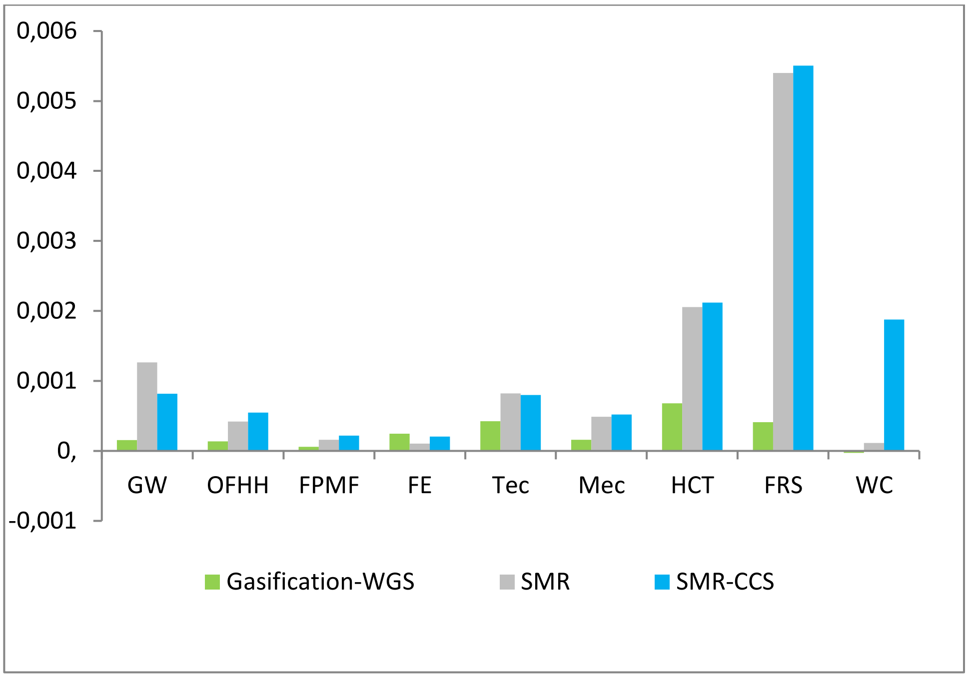

Figure 7: Comparison results of the LCIA of producing 1 Kg of hydrogen in the Brazilian context: Midpoint-Normalization

The results indicate that the Gasification-WGS outperforms the traditional natural gas-based method (SMR) in most environmental impact categories. The only exception to this trend is eutrophication (FE), which has a greater impact on Gasification-WGS. This is because eucalyptus cultivation involves the significant use of pesticides and herbicides, which together contribute to the release of substances rich in nitrogen and phosphorus into the environment. This flow of nutrients can increase the potential for eutrophication, highlighting the need for careful management of inputs into biomass production systems to mitigate these environmental impacts.

HCT is a significant impact in all scenarios, with higher values observed in the SMR-CCS due to the intensive use of natural gas and the chemical processes involved in carbon capture. In conventional SMR, the impact is lower but still notable, primarily due to the reliance on natural gas without the mitigation effect of carbon capture. Gasification-WGS stands out with the lowest HCT impact, largely because it uses biomass or alternative materials, which produce fewer carcinogenic by-products during processing.

FRS is the most significant impact across all categories. Both the SMR-CCS and conventional SMR exhibit the highest FRS impacts, driven by their heavy reliance on natural gas as a fossil resource and the substantial energy consumption required for the reforming and CO_2 capture processes. The need for large quantities of natural gas in these technologies results in higher depletion of fossil resources. Conversely, Gasification-WGS, which depend more on biomass and alternative materials, show relatively lower FRS impacts due to the more sustainable nature of the feedstocks used.

The WC is most pronounced in the SMR-CCS scenario, primarily due to the significant water usage for both CO_2 capture and steam generation during the methane reforming process. CO_2 capture is largely responsible for this impact, requiring large volumes of water to absorb the gas and regenerate the solvent. In the conventional SMR scenario, the WC impact is lower but still notable, primarily due to the steam production needed for the reforming process.

In Gasification-WGS, the water consumption impact is significantly lower, as the gasification process is more water-efficient compared to CO_2 capture. The biomass used in the process tends to have a more balanced water cycle, which results in lower overall water usage, contributing to a more sustainable scenario in terms of WC. This highlights the advantage of using biomass over fossil fuels in terms of water efficiency and sustainability.

The impact of GW is highest in the SMR scenario due to the heavy reliance on natural gas and the intensive CO_2 generation in the SMR process. Although SMR-CCS has a slightly lower impact, it still depends on natural gas and includes a CO_2 capture process that mitigates, but does not entirely eliminate, emissions from reforming. In Gasification-WGS, the impact is much smaller due to the use of eucalyptus biomass, which lowers net CO_2 emissions.

The SMR-CCS scenario stands out for a 35% reduction in CO_2 emissions, with 6,53 kg of CO_2 eq/kg H_2, in relation to the SMR scenario, which presents 10.1 kg of CO_2 eq/kg H_2. In contrast, the Gasification-WGS scenario presents a reduction of approximately 88%, resulting in 1.23 kg of CO_2 eq/kg H_2, standing out for its significantly lower environmental impact when compared to the other two scenarios.

These results are in line with the data found by Patel et al. (2024), who analyzed the emissions associated with the production of gray (SMR) and blue (SMR-CCS) hydrogen. According to their study, hydrogen production by the SMR process with natural gas resulted in 13.9 kg of CO_2 eq/kg H_2, in the LNG (liquefied natural gas) route and 12.3 kg CO_2 eq/kg H_2, in the pipeline route. In contrast, SMR-CCS presents a significant reduction in emissions, reaching 7.6 kg CO_2 eq/kg H_2, in the pipeline route and 9.3 kg CO_2 eq/kg H_2, in the LNG route, confirming that CCS reduces emissions, but the environmental impact is still higher compared to Gasification-WGS.

In a similar study, Buffi, Prussi and Scarlat, (2022) observed that hydrogen production from biomass gasification results in 2.14 kg of CO_2 eq/kg H_2, a value significantly lower than that of

SMR, whose emissions are 83.8% higher (13.3 kg CO_2 eq/kg H_2). This finding corroborates the results presented in this study, in which the Gasification-WGS scenario with eucalyptus biomass results in 1.23 kg of CO_2 eq/kg H_2, standing out as a more sustainable approach, compared to both gray hydrogen (SMR) and blue hydrogen (SMR-CCS).

Therefore, biomass gasification not only leads to a significant reduction in CO_2 emissions but also supports global emissions reduction goals. Using eucalyptus biomass, it exhibits a lower environmental impact compared to natural gas-based technologies, such as SMR and SMR-CCS, aligning with the transition to cleaner energy sources

3.4. Contribution analysis using endpoint normalization

The normalization results obtained through the *Endpoint ReCiPe (H) 2016* method for the three hydrogen production scenarios provide a clear perspective of the relative contribution of environmental impacts throughout their life cycles. Figure 8 presents a comparison of key environmental impact categories, illustrating significant differences in global environmental burdens, pollutant emissions, and natural resource consumption.

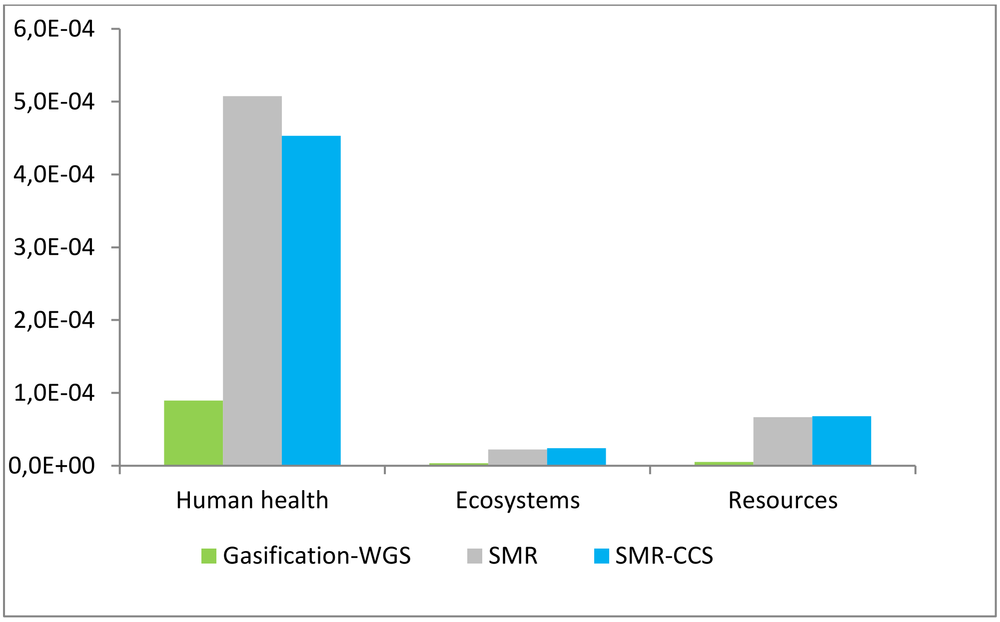

Figure 8: Comparison results of the LCIA of producing 1 Kg of hydrogen in the Brazilian context: endpoint-Normalization

The environmental impacts of the three hydrogen production scenarios were assessed in the categories of Ecosystem, Resources, and Human Health. The analysis reveals clear differences between the scenarios, with the Eucalyptus Gasification-WGS process presenting the lowest impacts across all categories.

Ecosystem Category: The Gasification-WGS scenario with Eucalyptus shows the lowest impact, with a value of 8,97E-05, significantly lower than SMR-CCS (4,53E-04) and SMR (5,07E-04). These results highlight the advantage of gasification, which causes much lower environmental impact on ecosystems compared to SMR processes. The impact of SMR-CCS is slightly higher than that of SMR, but still, the SMR scenario has the highest total impact. The largest difference is observed between gasification and SMR processes, reflecting the reduced impacts of gasification on ecosystems. This occurs because the gasification of biomass, such as eucalyptus, uses a renewable source that is less resource-intensive than fossil-based processes, resulting in lower emissions and environmental impacts.

Resources Category: In the Resources category, the Gasification-WGS scenario also shows the lowest impact, with a value of 7,1E-06, while SMR-CCS (7,0E-05) and SMR (6,66E-05) have significantly higher impacts. These data indicate that gasification is more efficient in terms of resource use, being less resource-intensive compared to SMR processes. The small difference between SMR and SMR-CCS can be attributed to the fact that while SMR-CCS captures some of the CO_2 emissions, it still relies heavily on natural gas, a non-renewable resource. The CO_2 capture and compression in SMR-CCS also require large amounts of energy, increasing the impacts in the Resources category.

Human Health Category: In the Human Health category, the results indicate that SMR and SMR-CCS have the highest impacts, with values of 5,07E-04 and 4,53E-04 respectively, while Gasification-WGS has the lowest impact, at 8,97E-05 Although the differences in human health impacts between the SMR and SMR-CCS scenarios are small, they are higher when compared to Gasification-WGS. This reflects the greater environmental impact associated with the combustion of fossil fuels, which contributes to the emission of pollutants harmful to human health, such as particulate matter and toxic compounds. The higher emissions of pollutants in SMR and SMR-CCS, especially from natural gas combustion and the need for energy generation, contribute to these impacts. However, all scenarios still show relatively low impacts in this category, indicating that hydrogen production, in general, has a limited effect on human health, but the eucalyptus gasification process stands out as being less polluting.

In summary, the environmental impact analysis highlights that although SMR and SMR-CCS exhibit slightly higher impacts in the Ecosystem, Resources, and Human Health categories, the eucalyptus gasification process emerges as a more sustainable option, with lower impacts across all evaluated categories. The use of biomass as feedstock for gasification reduces the reliance on fossil resources and minimizes pollutant emissions, making this process more environmentally friendly.

Regarding waste generated during the hydrogen production process, all scenarios produce byproducts such as residual gases, combustion ash, wastewater, and industrial solid waste. These wastes, if not properly managed, can contribute to ecosystem damage and resource depletion. For example, solid waste generated in the gasification of eucalyptus and in natural gas reforming processes may require special treatment to avoid soil and water contamination. Effective waste management is essential to minimize environmental impacts and ensure the sustainability of the processes.

4. LIMITATIONS

The main limitations of this study stem from assumptions made during the modeling process, the reliability of the data, and the chosen methodological approach. While reliable sources, such as the SimaPro Ecoinvent 3 databases, were utilized, it is important to acknowledge that the data may not fully represent the specific context of hydrogen production in Brazil. Primary data were prioritized where possible, but in many cases, secondary data from global or regional sources were used. The lack of detailed data on local eucalyptus cultivation practices and CCS in Brazil limits the accuracy of the analysis. Assumptions in the model include the efficiency of CCS technologies, based on global data, and the assumption that the eucalyptus gasification process aligns with global benchmarks, despite potential differences in local conditions in Brazil. Additionally, transportation distances for both natural gas and biomass were simplified, based on general scenarios, though they may vary depending on plant locations and available infrastructure.

To increase the accuracy and reliability of the results, the data should be constantly updated based on new available publications or possibly through new studies and practical measurements. Technological advances in production and energy conversion processes contained in the routes evaluated should also be computed in future studies.

5. CONCLUSIONS

This paper evaluated the environmental impacts of hydrogen production via three distinct technologies: Steam Methane Reforming (SMR), SMR with Carbon Capture and Storage (SMR-CCS), and Gasification with Water-Gas Shift (Gasification-WGS), using Life Cycle Assessment (LCA) across nine impact categories. The results highlight significant differences in their environmental performance, particularly in terms of Global Warming potential. Gasification-WGS produces 1,23 kg CO_2 eq/kg H_2, representing a substantial reduction compared to the 10.1 kg CO_2 eq/kg H_2 from SMR and 6.53 kg CO_2 eq/kg H_2 from SMR-CCS. This reduction is largely attributed to CO_2 absorption during biomass growth, demonstrating the potential of biomass-based hydrogen production to mitigate climate change. While SMR-CCS offers a 35% reduction in greenhouse gas emissions compared to conventional SMR, it still generates considerable impacts in other categories, such as resource depletion, due to the intensive energy demands of the CO_2 capture process.

The Gasification-WGS scenario shows promise as a cleaner alternative to fossil-based methods, but it faces challenges in areas like fertilizer use and electricity consumption. These impacts could be further mitigated by adopting more sustainable agricultural practices, optimizing energy efficiency, and improving resource management across the process. Despite these challenges, the lower emissions and reduced resource consumption of biomass gasification make it a more sustainable option in the long run. To further improve its environmental performance, focusing on reducing the toxicity of agricultural inputs and increasing the sustainability of farming practices will be key.

In conclusion, the analysis demonstrates that biomass-based hydrogen production, specifically through eucalyptus gasification, offers substantial reductions in environmental impacts and aligns with global decarbonization goals. Although this method is more sustainable than fossil-based alternatives like SMR and SMR-CCS, it still faces challenges, particularly regarding agricultural inputs and energy efficiency. Improving the sustainability of farming practices, such as minimizing the use of harmful fertilizers and pesticides, as well as optimizing energy consumption in the gasification process, will be crucial for maximizing its environmental benefits. By addressing these challenges, biomass gasification has the potential to contribute significantly to the global effort to reduce carbon emissions and transition to cleaner energy sources.

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7. APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://drive.google.com/drive/folders/1HZy42spDo-LnAnt4kay1vKTASb3K29bA?usp=drive_link

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PART 3: FINAL CONSIDERATIONS

This study evaluated, through LCA, three hydrogen production technologies in Brazil: eucalyptus biomass gasification and steam methane reforming of natural gas, with and without CCS. The results highlight Brazil's potential to advance toward a cleaner and more sustainable energy matrix, with the following conclusions:

1. **Environmental impacts and sustainability**
    - Eucalyptus biomass gasification exhibited the lowest emissions (1.84 kg CO_2 eq/kg H_2), due to carbon capture through eucalyptus cultivation, aligning with decarbonization goals.
    - Steam methane reforming of natural gas, even with CCS, had higher emissions, highlighting challenges in energy consumption and technology efficiency.
2. **Relevance for the Brazilian context**
    - The abundant eucalyptus biomass and the established infrastructure for natural gas provide a strategic opportunity for low-carbon solutions, positioning Brazil as a leader in climate change mitigation.
    - However, biomass transportation, logistical challenges in gasification, and the need to manage by-products such as tar still represent technical and economic barriers.
3. **Contributions of the research**
    - The study provides valuable insights for public policies and private initiatives promoting sustainable hydrogen technologies.
    - The integration of technical and environmental data aids in the planning of decarbonization strategies for the energy sector, meeting global demand for cleaner energy.

SUGGESTIONS

Future research could focus on improving the energy efficiency of biomass gasification by investigating advanced catalysts and heat recovery systems. Additionally, exploring the integration of biomass gasification with CCS could enhance environmental benefits. Conducting detailed techno-economic feasibility studies is also essential, taking into account investment, operation, and maintenance costs at a commercial scale. Furthermore, it is important to assess the social and economic impacts of adopting hydrogen production technologies, particularly in regions dependent on biomass. Finally, investigating the combination of hydrogen with other renewable energy sources, such as solar and wind, could strengthen the energy matrix and promote a more resilient energy system.