

FEDERAL UNIVERSITY OF ITAJUBÁ (Unifei)
ENERGY ENGINEERING MASTER'S DEGREE COURSE (PPGEEN)
INSTITUTIONAL HUMAN RESOURCES TRAINING PROGRAM OF THE NATIONAL PETROLEUM,
NATURAL GAS AND BIOFUELS AGENCY (PRH-ANP N° 46.1)

Douglas Peterson Munis da Silva

**INTEGRATED ASSESSMENT OF HYDROGEN PRODUCTION AND USE IN
BRAZIL: ENVIRONMENTAL PERFORMANCE, ECONOMIC FEASIBILITY AND
SOCIAL BENEFITS**

Document for the Energy Engineering master's
degree Course as part of the requirements for
obtaining the degree of Master in Energy
Engineering

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Co – supervisor: Moisés Diniz Vassallo

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Itajubá-MG

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Douglas Peterson Munis da Silva

AVALIAÇÃO INTEGRADA DA PRODUÇÃO E USO DE HIDROGÊNIO NO
BRASIL: PERFORMANCE AMBIENTAL, VIABILIDADE ECONÔMICA E
BENEFÍCIOS SOCIAIS

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ABSTRACT

This work presents an integrated assessment of hydrogen (H_2) production and use in Brazil, simultaneously addressing environmental performance, economic feasibility, and socioeconomic benefits. The Life Cycle Assessment (LCA) tool was applied from a “cradle-to-gate” perspective to compare seven H_2 production pathways: water electrolysis powered by wind energy, photovoltaic energy, and the Brazilian power grid; and steam reforming of natural gas, sugarcane ethanol, corn ethanol, and landfill biomethane. Three environmental indicators were evaluated: Global Warming Potential (GWP), Water Scarcity Footprint (WSF), and Fossil Energy Ratio (FER). The results revealed a wide range of impacts across the pathways: GWP varied between 0.6 kg $CO_{2eq}/kg H_2$ and 39.1 kg $CO_{2eq}/kg H_2$, for electrolysis powered by wind, and the Brazilian power grid for the marginal operation (solely based on natural gas), respectively. WSF ranged from 0.4 for the natural gas-based pathway to 60.9 $m^3 H_2O_{eq}/kg H_2$ for the photovoltaic-based electrolysis route with battery storage. This variation indicates that renewable-based routes, when battery systems are coupled in H_2 production, can also be water-intensive. FER showed that even renewable routes still have an indirect dependence on fossil fuels, mainly associated with equipment manufacturing. The lowest GWP was evaluated for H_2 derived from wind and PV electricity, however, the analysis of the environmental normalized indicators showed that biomethane and wind-powered electrolysis presented the best overall performance, followed by the steam reforming of sugarcane ethanol. Regarding the use of H_2 , this work evaluated the potential macroeconomic effects derived from ammonia (NH_3) produced using wind and PV electricity. NH_3 is a feasible alternative for storing and transporting H_2 and, also, it is an important input as fertilizer for agricultural. However, even though the renewable energy availability in Brazil for producing NH_3 , it still has a strong dependence on imports of NH_3 . In this way, from an economic perspective, the levelized cost of electrolytic H_2 (LCOH) and its derivative NH_3 (LCOA) were estimated. LCOH range from 3.30 to 6.94 USD/kg H_2 and LCOA varied between 778.2 to 1,908 USD/t NH_3 , depending on the electricity source. For NH_3 , projected costs remain around 62% higher than fossil-based NH_3 , reinforcing the need for incentive policies. Regarding socioeconomic aspects, the results showed that a domestic low-carbon H_2 and NH_3 value chain could result into negative economic effects, suggesting that the energy transition should be financed through a diversified set of instruments, such as carbon pricing, tariffs on fossil products, and incentives for domestic production of electrolyzers and photovoltaic panels. It is concluded that Brazil has high technical potential to become a relevant player in the global low-carbon H_2 and NH_3 market but

faces structural challenges to consolidating a competitive industry. Partial localization of the supply chain can reduce costs, increase socioeconomic benefits, and align the country with decarbonization targets. This research underscores the need for an integrated national strategy combining industrial, energy, and agricultural policies to enable the transition to a low-carbon economy based on low-carbon H₂.

RESUMO

Este trabalho apresenta uma avaliação integrada da produção e uso de hidrogênio (H_2) no Brasil, abordando simultaneamente o desempenho ambiental, a viabilidade econômica e os benefícios socioeconômicos. A metodologia de Avaliação do Ciclo de Vida (ACV) foi aplicada sob a perspectiva “do berço ao portão” para comparar sete rotas de produção de H_2 : eletrólise da água alimentada por energia eólica, energia fotovoltaica e pela rede elétrica brasileira; e reforma a vapor de gás natural, etanol de cana-de-açúcar, etanol de milho e biometano de aterros sanitários. Três indicadores ambientais foram avaliados: Potencial de Aquecimento Global (GWP), Pegada de Escassez de Água (WSF) e Requisito de Energia Fóssil (FER). Os resultados revelaram uma ampla variação de impactos entre as rotas: o GWP variou entre 0,6 kg CO_{2eq} /kg H_2 e 39,1 kg CO_{2eq} /kg H_2 , para eletrólise alimentada por energia eólica, e para a operação marginal da rede elétrica brasileira (baseada exclusivamente em gás natural), respectivamente. O WSF variou de 0,4 para a rota baseada em gás natural até 60,9 m³ H_2O_{eq} /kg H_2 para a rota de eletrólise fotovoltaica com armazenamento em baterias. Essa diferença indica que rotas renováveis, quando acopladas a sistemas de baterias na produção de H_2 , podem também ser intensivas em uso de água. O FER demonstrou que mesmo nas rotas renováveis ainda existe uma dependência indireta de combustíveis fósseis, principalmente associada à fabricação de equipamentos. O menor GWP foi avaliado para o H_2 derivado de eletricidade eólica e fotovoltaica; entretanto, a análise dos indicadores ambientais normalizados mostrou que o biometano e a eletrólise alimentada por energia eólica apresentaram o melhor desempenho global, seguidos pela reforma a vapor do etanol de cana-de-açúcar. Em relação ao uso do hidrogênio, este trabalho avaliou os potenciais efeitos macroeconômicos derivados da amônia (NH_3) produzida utilizando eletricidade eólica e fotovoltaica. A NH_3 é uma alternativa viável para o armazenamento e transporte de H_2 , além de ser um insumo importante como fertilizante para a agricultura. Contudo, mesmo com a disponibilidade de energia renovável no Brasil para produzir NH_3 , o país ainda depende fortemente da importação de NH_3 . Assim, sob a perspectiva econômica, foram estimados os custos nivelados do H_2 eletrolítico (LCOH) e de da NH_3 (LCOA). O LCOH variou de 3,30 a 6,94 USD/kg H_2 e o LCOA de 778,2 a 1.908,0 USD/t NH_3 , dependendo da fonte de eletricidade. Para a NH_3 , os custos projetados permanecem cerca de 62% superiores ao da NH_3 fóssil NH_3 , reforçando a necessidade de políticas de incentivo. No que se refere aos aspectos socioeconômicos, os resultados mostraram que uma cadeia nacional de valor de H_2 e NH_3 de baixo carbono poderia resultar em impactos negativos, sugerindo que a transição energética deve ser financiada por um conjunto diversificado de

instrumentos, como precificação de carbono, tarifas sobre produtos fósseis e incentivos à produção nacional de eletrolisadores e painéis fotovoltaicos. Conclui-se que o Brasil possui alto potencial técnico para se tornar um player relevante no mercado global de H_2 e NH_3 de baixo carbono, mas enfrenta desafios estruturais para consolidar uma indústria competitiva. A localização parcial da cadeia de suprimentos pode reduzir custos, aumentar os benefícios socioeconômicos e alinhar o país às metas de descarbonização. Esta pesquisa reforça a necessidade de uma estratégia nacional integrada, combinando políticas industriais, energéticas e agrícolas para viabilizar a transição para uma economia de baixo carbono baseada no H_2 de baixo carbono.

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1 INTRODUCTION

The rapid growth of cities and populations led to a 38% increase in energy demands between 2000 and 2013 (Da Silva Veras *et al.*, 2017), raising concerns about ongoing reliance on fossil fuels and the rise in the Earth's temperature (Aravindan; Kumar, 2023; Wijayasekera *et al.*, 2022). Local governments world-wide have pointed out energy security as a critical issue in ensuring a clean and reliable energy supply. In this context, a sustainable energy transition - driven by the increased use of renewable resources and the development of more efficient, sustainable processes - is therefore essential (Moura; Silveira; Lamas, 2020; Prato-Garcia; Robayo-Avenidaño; Vasquez-Medrano, 2023).

As concerns about climate change and energy security continue to grow (Cetinkaya; Dincer; Naterer, 2012), the development of renewable energy systems (RES) has become a key strategy. The harmful effects of fossil fuel combustion on the environment and human health highlight the urgent need to transition to a clean energy system that reduces the dependence on fossil fuels (Zhang; Yang, 2022).

To meet greenhouse gas (GHG) emissions reduction targets, it is estimated that by 2050, RES must account for at least 12% of total energy consumption - six times the current final global demand (Hassan *et al.*, 2023). In addition, many regions are experiencing water scarcity due to climate issues (Mir; Nurdiawati; Al-Ghamdi, 2025). Given that the energy sector relies heavily on the availability of water resources, assessing water availability and scarcity as well as GHG emissions for energy sources is crucial (Olaitan; Bertagni; Porporato, 2024).

GHG emissions, primarily from the use of fossil fuels in electricity generation, industry, and heating, are the main contributors to changes in climate dynamics, as over 80% of global energy needs are met by fossil fuels, including oil, coal, and natural gas (Gandiglio *et al.*, 2022). In 2020, GHG emissions from energy systems accounted for 73.3% of total global emissions (Ritchie; Roser; Rosado, 2024).

In this sense, it is clear that the energy sector is the largest contributor to the increase in GHGs in the atmosphere (EPE, 2023a). Therefore, reducing them is a global priority (Wedy; Amaral; Pimentel, 2022). By developing RES is possible to shifted away from a fossil fuel-dependent economy and move toward cleaner energy sources with lower environmental impacts (Santos *et al.*, 2020).

According to the International Renewable Energy Agency (IRENA), renewable energy generation will play a crucial role in achieving GHG targets by 2050, contributing to 41% of the total reduction, while energy efficiency initiatives will account for 40% of decarbonization efforts (IRENA, 2018). With global energy needs projected to grow by 48% over the next 20 years due to population growth (Chelvam *et al.*, 2024), the focus on alternative, and renewable energy sources (RES) is intensifying (Da Silva Veras *et al.*, 2017).

In this context, low-carbon H₂ could play a key role in transforming the current energy system. Low-emission H₂ is expected to contribute to decarbonizing energy systems, especially in hard-to-abate

sectors, e.g., in cement production (Palmer *et al.*, 2021). H₂ energy systems have the potential to reshape the energy landscape by driving market growth through competitive pricing, improved quality, enhanced energy security, and advancements in renewable energy technologies (Arvesen; Hertwich, 2011; Oliveira, 2022). H₂ has been identified as a powerful catalyst for advancing toward a low-carbon society, thanks to its diverse applications and the fact that its combustion produces only water as a by-product (Santos *et al.*, 2017; Yue *et al.*, 2021).

According to Hren *et al.* (2023), H₂ usage can be categorized into three main areas: first, it is used as a reagent in hydrogenation processes, accounting for nearly 65% of H₂ consumed in the production of chemicals like ammonia, methanol, hydrochloric acid, hydrogen peroxide, and others; second, 25% H₂ production is applied to oil refining, petrochemical production, fertilizer hydrogenation, and metallurgical processes and finally, the remaining 10% of the global H₂ supply is used as an oxygen removal agent, in internal combustion engines, and as a cooling refrigerant in electricity generation and weather balloons. Only a small proportion is used for energy purposes - over 90% of H₂ is used for traditional industrial purposes (IEA, 2019; Nadaleti; Borges dos Santos; Lourenço, 2020).

Currently, most H₂ is produced from fossil fuels, e.g., natural gas and coal, through steam reforming and gasification processes, which account for 60% and 20% of global H₂ production, respectively (IEA, 2024b). By contrast, low-emission H₂ makes up less than 1% of global production (IEA, 2024b). This underscores the need to develop and scale up clean H₂ production systems, alongside enhancing the infrastructure for storage, transportation, and final applications.

Depending on the resources and technologies used for H₂ production, it can be categorized as grey, green, or blue energy (Ajanovic; Sayer; Haas, 2022; Chew *et al.*, 2023; Incer-Valverde *et al.*, 2023). Grey H₂ is produced from fossil fuels (natural gas or coal) through steam methane reforming (SMR) and coal gasification (CG) (Ajanovic; Sayer; Haas, 2022). SMR it's a well-established, cost-effective method, but it comes with significant environmental concerns due to high GHG emissions (Rojas *et al.*, 2023; Zhang *et al.*, 2024). Blue H₂ is produced from fossil fuels with the addition of carbon capture and storage (CCS), while green H₂ comes from renewable sources such as wind and solar energy (Osman *et al.*, 2022).

H₂ systems are particularly benefit when integrated with RES. H₂ can be converted into electricity, making it a highly versatile energy carrier (Ergin Şahin, 2020). It serves as a clean fuel for vehicles, offering an environmentally friendly alternative to conventional fossil fuels and significantly reducing GHG emissions (Hren *et al.*, 2023). Furthermore, H₂ plays a key role in stabilizing RES by storing and releasing energy. This capability helps smooth out the variability of RES, ensuring energy security, adaptability, and stability in these systems (Gandiglio *et al.*, 2022).

Hydrogen based energy systems are often evaluated mainly from a GHG emissions perspective, as reducing emissions is a key driver for promoting H₂ (Martinez *et al.*, 2024). Many studies agree that H₂ derived from fossil fuels should be avoided due to the high GHG emissions associated with its

production (Antonini *et al.*, 2020; Aydin; Dincer, 2022; Hajjaji *et al.*, 2013; Hren *et al.*, 2023; Khila *et al.*, 2016; Patel *et al.*, 2024; Sadeghi; Ghandehariun; Rosen, 2020; Suleman; Dincer; Agelin-Chaab, 2016; Valente *et al.*, 2020).

For instance, several studies have highlighted the significant consumption of fossil resources throughout the life cycle of renewable H₂ systems, pointing out their ongoing reliance on fossil fuels even in green H₂ production (Cvetković *et al.*, 2021; Hajjaji *et al.*, 2016b; Mio *et al.*, 2024; Tripathi; Subramanian, 2022; Wijayasekera *et al.*, 2022). As a result, evaluating energy performance is crucial for reducing dependence on fossil fuels while boosting energy output.

On the other hand, some research has explored water related challenges in H₂ production (Cui *et al.*, 2021; De Souza *et al.*, 2021; Henriksen *et al.*, 2023; Olaitan; Bertagni; Porporato, 2024; Shi; Liao; Li, 2020). In this way, assessing WC across the entire life cycle of H₂ is key to understanding its potential impacts on environmental sustainability and water resource management.

As the development of renewable H₂ systems accelerates, assessing the potential environmental impacts of these systems has become crucial. Scientific studies have examined the environmental performance of H₂ systems, focusing on the individual assessment of indicators such GHG emissions (Rojas *et al.*, 2023; Valente; Iribarren; Dufour, 2020; Weidner; Tulus; Guillén-Gosálbez, 2023), water consumption (WC) (Cui *et al.*, 2021; Du *et al.*, 2024; IRENA; Bluerisk, 2023), water scarcity footprint (WSF) (Du *et al.*, 2024; Simoes *et al.*, 2021), and energy efficiency (Li *et al.*, 2020), thus, neglecting the relationship between GHG emissions, energy performance and WC and WSF.

The Sustainable Development Goals, instituted by the United Nations, emphasize the significance of improving energy efficiency, advocating for the sustainable utilization of energy and renewable resources (Goal 7), mitigating GHG emissions to address climate change (Goal 13), and guaranteeing the accessibility and sustainable management of water and sanitation for all individuals (Goal 6) (Maziotis *et al.*, 2024). In this regard, the assessment of the Energy-Carbon-Water nexus aims to optimize the use of energy and water resources, and at the same time, reducing carbon emissions, thus mitigating global climate impacts (Faezi; Poursadegh; Barati, 2025; Li; Zhao; Lin, 2020).

As discussed previously, one of the most promising short-term applications for H₂ is the utilization of its high energy storage capacity. Considering that one of the main challenges associated with RES lies in energy storage methods, chemical energy storage systems – such as hydrogen and ammonia - can enhance the flexibility of these sources (María Villarreal Vives *et al.*, 2023), while enabling the storage of large amounts of energy due to their high energy density (Smith; Hill; Torrente-Murciano, 2020).

Despite the energy content per mass unit of H₂ which make it a suitable source for energy storage, its low volumetric energy density at mild temperature and pressure conditions, H₂ storage and distribution become a challenge (Arnaiz Del Pozo; Cloete, 2022). Safe and economic technologies for H₂ transportation are still under development (Sánchez *et al.*, 2021). Compressed H₂ (up to 900 bar) can

consume about 18% of its Lower Heating Value (LHV), while for liquefied H₂ transportation, energy consumption can reach up to 45% of its LHV (Aba; Sauer; Amado, 2024).

In this way, to overcome challenges in the H₂ supply chain, H₂ can be converted into ammonia (NH₃) through a process known as Power-to-Ammonia (PtA). NH₃ contains high levels of H₂ content, and it can be stored in liquid form under mild temperature and pressure conditions (Bicer; Dincer, 2018; Nguyen *et al.*, 2025). Furthermore, NH₃ has a volumetric energy density approximately 50% higher than H₂, and it can be transported relatively easily at -33 °C or under pressures below 10 bar (Kelman *et al.*, 2020; María Villarreal Vives *et al.*, 2023) making it a feasible option for H₂ storage and transportation (Acar, 2018).

This study aims to explore potential trade-offs among GHG emissions, fossil energy consumption, and water scarcity associated with H₂ production. The integrated assessment of these environmental indicators has become essential for meeting environmental targets, given the interdependent nature of sustainability metrics (Elaouzy; El Fadar, 2024; Maziotis *et al.*, 2024; Silva; Capaz, 2025). The study also evaluates the levelized cost of H₂ and NH₃ production through electrolysis under Brazilian conditions and estimates the potential macroeconomic impacts - such as employment generation, income, and GDP - arising from the conversion of H₂ into its derivative, NH₃.

2 OBJECTIVES

This study examines the sustainability of the Brazilian H₂ supply chain. It covers two key areas: (i) environmental analysis of H₂ production methods, noting trade-offs; and (ii) socioeconomic effects of using H₂ to produce NH₃. The specific objectives include:

- Describe potential pathways for H₂ production in Brazilian conditions.
- Describe the H₂ usage for NH₃ production.
- Evaluate possible *trade-offs* in H₂ production pathways considering GHG emissions, water use and fossil energy dependence.
- Estimate the levelized cost of H₂ (LCOH) and electrolytic NH₃ (LCOA).
- Estimate the potential socioeconomic impacts of applying H₂ for NH₃ synthesis in Brazil.

3 LITERATURE REVIEW

This section highlights the role of low-carbon H₂ in promoting the decarbonization of the energy sector. It discusses its main production pathways – from both fossil and renewable resources – as well as its potential applications and the logistical challenges associated with this energy carrier.

3.1. Hydrogen production pathways

As concern about climate issues and energy security grow, low-carbon H₂ has been pointed out as an option for accelerating a sustainable energy transition. H₂ stands out due to its high energy storage capacity, making it a viable solution for guaranteeing reliability and flexibility in electrical systems (Brandon; Kurban, 2017). Also, low-carbon H₂ can help to achieve the economy decarbonization as well as reducing resources consumption as water and fuels (Mehmeti *et al.*, 2018; Olaitan; Bertagni; Porporato, 2024).

At industrial level, H₂ can be produced from two main methods: thermochemical and electrolytic. Each method uses different energy sources (Zhang *et al.*, 2024). While interest in producing H₂ from renewable sources is growing, only a small fraction - just 1% - is currently produced using clean energy (Nadaleti; Borges dos Santos; Lourenço, 2020).

Various renewable methods production exist but the most common focus on converting electricity into the desired energy resource, a process known as “Power-to-X”, where “X” represents the specific energy type or application (GIZ, 2021). For example, “Power-to-Gas” method involves converting electricity into gaseous fuels like H₂ or synthetic fuels such as ammonia, methane, and aviation fuel and “Power-to-Power” refers to converting the chemical energy in H₂ back into electricity (Hassan *et al.*, 2023; Yue *et al.*, 2021).

In this work, the main production stages considered in LCA studies reviewed are show in Figure 1. Renewable sources for H₂ synthesis are labeled as green boxes and non-renewable, as grey boxes. The energy efficiency related to the H₂ technology conversion were based on (Ghasemi; Nikafshan Rad; Akrami, 2024; Hajjaji *et al.*, 2016b, 2016a; Shaya; Glöser-Chahoud, 2024).

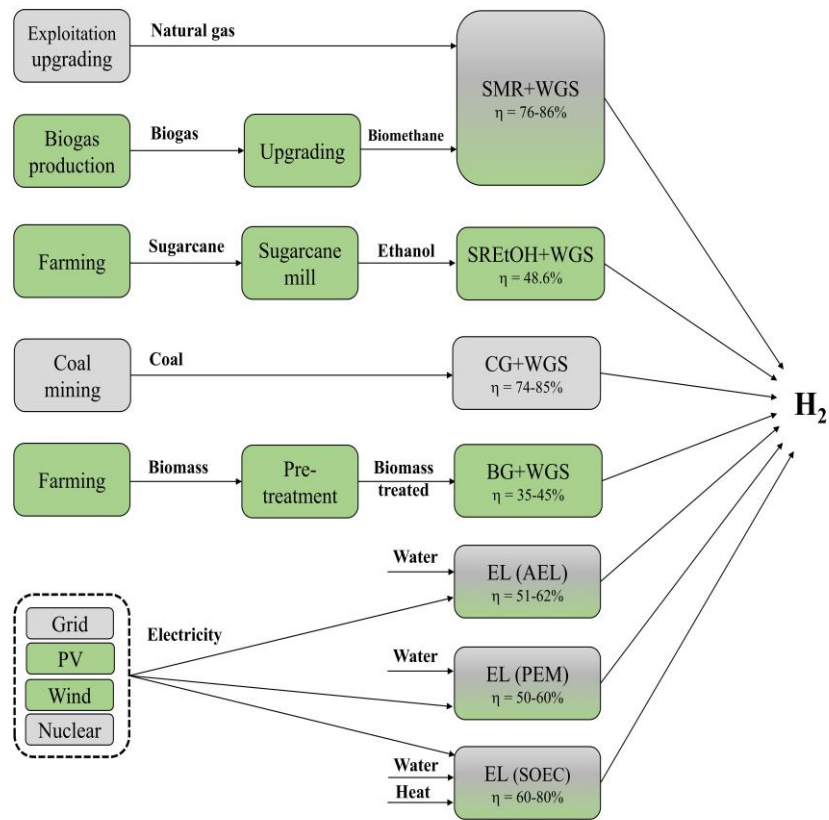


Figure 1 – Main stages typically assumed for LCA¹

Source: Own elaboration

The current study selected H₂ production pathways with high level of maturity, as reported by Ghasemi, Nikafshan Rad and Akrami (2024) and Shaya and Glöser-Chahoud (2024).

3.1.1. Steam Reforming Process

As mentioned above, steam reforming of natural gas (SMR) is the most common and developed technique for producing H₂. In SMR, natural gas, and other hydrocarbons are converted into synthesis gas through an endothermic process involving two main reactions: steam reforming and the water–gas shift (WGS) reaction (Hren *et al.*, 2023).

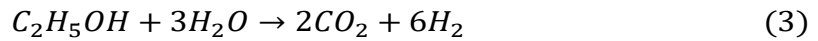
In the reformer unit, treated natural gas reacts with water to produce syngas, a gaseous mixture of H₂, CO, and CO₂. The CO in the syngas reacts with water in an exothermic WGS reaction, increasing the H₂ concentration and improving the overall efficiency of SMR (Hren *et al.*, 2023; Ji; Wang, 2021; Mio *et al.*, 2023).

¹ Main stages typically assumed for life cycle assessments of H₂ production pathways. Green and Grey boxes indicate processes mainly based on renewable resources or non-renewable resources, respectively; AEL: Alkaline Electrolysis; BG: Biomass Gasification; CG: Coal Gasification; EL: Water electrolysis; PEM: Proton Exchange Membrane; PV: photovoltaic system; SMR: Steam Methane Reforming; SOEC: Solid Oxide Electrolysis; SREtOH: Steam Reforming of Ethanol; WGS: Water-Gas-Shift process.

To enhance the purity of the H₂ and remove other gases, the H₂ directed goes through a pressure swing adsorption (PSA) unit, which separates it from CO₂, achieving H₂ purity levels of up to 99.95% (Hren *et al.*, 2023; Luk *et al.*, 2012; Prato-Garcia; Robayo-Avendaño; Vasquez-Medrano, 2023). Syngas, the precursor to H₂, can also be generated from renewable resources such as ethanol (EtOH) and biomethane (Yue *et al.*, 2021). Typical natural gas reform is shown in Eq. (1) and Eq. (2), as follows:



In this context, steam reforming can use ethanol (SREtOH) as both a raw material and an energy source for H₂ generation (Argonne National Laboratory, 2023). EtOH reacts with steam to produce syngas, and any remaining CO in the syngas is converted into CO₂ and more H₂ through the WGS reaction (Hajjaji *et al.*, 2016a; Mehmeti *et al.*, 2018). The equations (3) and (4) below are the general reaction of EtOH reforming:



Several advantages exist for using EtOH as feedstock for H₂ synthesis: diverse biomass sources for EtOH production (Palanisamy; Soundarrajan; Ramasamy, 2021); high H₂ content - 3H₂:1CO₂ (Llorca *et al.*, 2013); iii. extensive distribution network for EtOH already exists and convenient storage and low toxicity due to EtOH it is easily stored and has low toxicity (Hajjaji *et al.*, 2016a).

Furthermore, converting EtOH to H₂ cuts the need for the purification and dehydration steps required for certain ethanol applications, such as blending with gasoline. These processes can consume up to three-quarters of the energy used in EtOH production (Hajjaji *et al.*, 2016a).

In addition to climate concerns, increases in solid waste generation constitute a significant challenge. Poor waste management practices negatively impact to public health and contribute to soil and water pollution (Wijayasekera *et al.*, 2022). Using waste for energy provides a solution to both waste management issues and GHG emissions, which account for about 5% of global emissions (Cho; Strezov; Evans, 2023).

The process of generating H₂ from biogas is similar to that from natural gas, though it requires additional purification and treatment steps for biogas purification (Borole; Greig, 2019; Lo Basso *et al.*, 2023). The equation (5) below is a demonstration of the biomethane reforming process (SRBiogas):



Converting waste into biogas, which is made up of methane (50 – 80%) and carbon dioxide (20 – 50%) with other trace gases (Hammi *et al.*, 2024), is one method for producing H₂ through steam reforming. Biogas can be derived from various waste sources, including organic waste, agricultural waste, landfill sites, and sewage treatment waste, as a byproduct of anaerobic digestion.

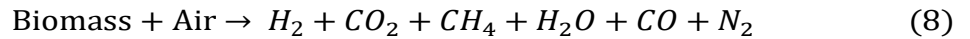
3.1.2. Coal Gasification Process

Coal gasification (CG) is a widely used technology for producing inexpensive and efficient H₂. In this process, coal reacts with oxygen in low concentrations, combined with steam, under high temperature and pressure to produce syngas (Mehmeti *et al.*, 2018). The CO present in syngas can be converted to improve process efficiency through the WGS reaction, which increases the H₂ production rate (Busch; Kendall; Lipman, 2023). Efficiency ranges between 74% – 85% (Hammi *et al.*, 2024). Typical CG processes are shown below:



The gasification method has gained interest because it can employ both renewable and non-renewable materials (Maniscalco *et al.*, 2024). Gasification can use any carbon-based material such as coal, car tires, sewage sludge, sawdust, wood and plastic waste (Midilli *et al.*, 2021). Gasification may produce other trace gases along H₂ (CO, CH₄, H₂S, NH₃, HCl, HCN, ash and tar) becoming necessary purification steps to enhance the purity of the gas (Cui *et al.*, 2022).

Biomass can also be employed for H₂ generation through the gasification process. Biomass is broken in high temperatures in low-oxygen atmosphere (Ghasemi; Nikafshan Rad; Akrami, 2024). A typical reaction for biomass gasification (BG) is the following:



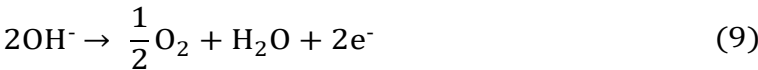
Tar can be produced concurrently with the production of H₂ (Ghasemi; Nikafshan Rad; Akrami, 2024).

3.1.3. Electrolysis Process

In addition to the thermochemical pathways mentioned above, electrochemical methods that use

water and electricity to produce H₂ are also noteworthy. These methods can reduce GHG emissions by nearly 90% compared to traditional fossil fuel-based methods (Cho; Strezov; Evans, 2023).

Electrolysis (EL), an electrochemical method, involves converting electricity into H₂ by splitting water into H₂ and O₂ molecules when an electrical current is passed through water (Chi; Yu, 2018; Palmer *et al.*, 2021). An ion-separating membrane is placed in the water to facilitate the separation of H₂ gas produced at the cathode from O₂ produced at the anode (Simons; Bauer, 2011). Efficiency ranges between 60% - 80% (Chang; Rajuli, 2024, p. 202). The equations (9) and (10) below present the reactions that occur in the electrolysis process:



Currently, three main commercial methods for producing H₂ through electrolysis are in use: alkaline electrolysis (AEL), which leads the H₂ market and has been in development for several years (Zhang *et al.*, 2022); solid oxide electrolysis (SOEC), which operates at high temperatures to break down water molecules without requiring significant electricity (Yue *et al.*, 2021); and proton exchange membrane (PEM) electrolysis which offers greater operational flexibility and the ability to handle variable loads, making it ideal for systems that rely on intermittent energy sources (Palmer *et al.*, 2021). Table 1 shows the main differences between electrolysis technologies.

Table 1 – Comparison of key water electrolysis technologies

Electrolyzer	Technology maturity	Efficiency (%)	Operating temperature (°C)	System lifetime (h)	Advantages	Disadvantages	Sources
AEL	Mature	61 - 82	70 – 90	60,000 – 90,000	Proven technology Cost-effective solution Efficient performance Robust and durable Scalable design Supports megawatt-range stack configurations Optimized materials Bipolar plates High-performance catalyst	Limited current density Lower H ₂ purity Corrosive electrolyte Reduced operational flexibility Narrow partial load range Low operating pressure Gas crossover risk	(Chelvam <i>et al.</i> , 2024; Ergin Şahin, 2020; Hammi <i>et al.</i> , 2024; Osman <i>et al.</i> , 2022; Shaya; Glöser-Chahoud, 2024; Yue <i>et al.</i> , 2021)
PEM	Small scale	50 – 60	50 – 80	20,000 – 60,000	High current density Excellent voltage efficiency Wide partial load range Compact system architecture	Emerging technology High component costs Corrosive operating environment Limited durability	

Electrolyzer	Technology maturity	Efficiency (%)	Operating temperature (°C)	System lifetime (h)	Advantages	Disadvantages	Sources
SOEC	In the near term	60 – 80	700 – 850	10,000	High-purity H ₂ output Superior dynamic performance Fast startup time Advanced electrode materials Gas diffusion layer Durable sealing materials	Smaller stack sizes Membrane limitations Operates at higher pressures Dependence on noble metal catalysts	
					Exceptional efficiency Non-noble metal catalysts High-pressure operation Advanced electrode material Efficient gas diffusion layer	Thermal and material limitations High operating temperatures Bulky system design Lack of cathode diffusion layer Fragile sealing materials	

Source: Own elaboration

Different levels of technological maturity among electrolyzer types highlight the various possibilities for producing H₂ from electricity and water, with each technology presenting its own potential and challenges. Also, the growing capacity of RES like wind and solar is driven by lower costs and increasing demand, leading to reduced costs in the renewable sector (Aravindan; Kumar, 2023) which can enhance EL systems and reduce H₂ cost production (Terlouw *et al.*, 2022).

A key consideration in EL systems is the potential market for the O₂ produced alongside H₂, which can yield approximately 8.0 kg of O₂ for every kg of H₂. This O₂ has applications across various sectors, including steel, pulp and paper, chemical, healthcare, and ozonation-based water treatments. However, with the expected increase in EL systems, the market for the generated O₂ may become insufficient (Nicita *et al.*, 2020).

3.2. Life Cycle Assessment Review

The pressing issue of product and process sustainability has sparked the creation of a multitude of methodologies aimed at assessing the environmental impact of products prominently featuring Life Cycle Assessment (LCA), which identifies and scrutinizes potential environmental aspects and impacts across the full life span of a product or service (Von Der Assen; Jung; Bardow, 2013).

LCA serves as a powerful tool to shape and oversee public policies, proving invaluable in the industrial sector by enhancing decision-making, fostering the development and selection of indicators for environmental performance monitoring, and guiding the discovery of alternatives or pathways that significantly mitigate negative impacts or resource depletion, while also facilitating comparisons of processes to pinpoint the option with the least environmental footprint (Godskesen; Meron; Rygaard,

2018). A LCA study comprises four critical stages: the definition of objective and scope, the inventory analysis, the impact assessment, and the interpretation phase (ISO, 2006, p. 14040).

LCA outcomes can help assess the impacts of producing and using a product or service; compare methods to aid in selecting the optimal approach; identify critical stages to reduce impacts throughout the production process; and guide planning and decision-making. Some methodological choices influence LCA results. In this sense, this work, wherever was possible, identified the key parameters, such as system boundaries, functional unit and allocation methods from the selected papers for providing a broader discussion.

The potential environmental impacts of the H₂ production can be assessed using LCA (Terlouw *et al.*, 2022; Zhang *et al.*, 2022). As interest in H₂ as an energy resource grows, research employing LCA is increasingly supporting decision-making about the best methods and resources for its production (Gandiglio *et al.*, 2022).

In LCA analysis, there are several methods to estimate the WC of a product, either based on the water resources consumption (referred to as the Water Footprint Assessment, WFA) (Hoekstra *et al.*, 2012) or on the environmental impacts resulting from water consumption (Boulay *et al.*, 2018).

The first approach focuses on the volumetric water demand for producing goods and services; while the second, mostly based on the Available Water Remaining (AWARE) method, is an environmental impact indicator that estimates the Water Scarcity Footprint (WSF). WSF is defined as the amount of available water per area after human and ecosystem needs are met (García-Herrero *et al.*, 2023).

AWARE is recommended by the Life Cycle Initiative of the UN Environment Programme (UNEP) for calculating water scarcity (Boulay; Lenoir, 2020). This method considers both human and ecosystem water deprivation, assuming that the less water remaining per area, the more users in that area will experience freshwater shortages (Ansorge; Beránková, 2017).

The second approach, WFA proposed by Hoekstra (Hoekstra *et al.*, 2012) assess three different types of water: blue water (which refers to fresh surface or groundwater), green water (which accounts for precipitation that does not run off or the volume of water that is stored in the soil) and grey water (which is defined as the volume of freshwater that is required to assimilate the load of pollutants) (Hoekstra *et al.*, 2012).

The energy demand for a product can also be assessed through LCA. It serves as a broad indicator for evaluating primary energy consumption throughout its entire life cycle (Burkhardt *et al.*, 2016). Cumulative Energy Demand (CED) is a valuable metric for assessing the energy required (renewable and non-renewable) in the extraction, manufacturing, operation, and final disposal of resources through its lifetime (Huijbregts *et al.*, 2010). However, CED should be considered alongside other environmental indicators, such as global warming potential (GWP), due to its interrelationship with these factors (Dufour *et al.*, 2012; Simons; Bauer, 2011).

An indicator derived from CED is the Energy Return on Investment (EROI), which measures the energy profitability of an energy system (Murphy *et al.*, 2022). EROI represents the ratio of useful energy produced by an energy system over its lifetime to the energy invested or consumed during its operation (Aba; Sauer; Amado, 2024; Mio *et al.*, 2023; Zhang *et al.*, 2023). EROI is useful for evaluating energy performance and assessing the environmental impact of the energy system (Murphy *et al.*, 2022).

To achieve consistency in the findings, the current study have extracted data pertaining to fossil energy consumption associated with H₂ production from each analyzed research, thereby facilitating the estimation of the correlation between the energy yield embodied in 1 kg of H₂ (based on the LHV H₂) and the fossil energy consumption across the entire life cycle, or alternatively, derived from the fossil CED. This correlation has been designated as an energy indicator (EI) within the scope of this analysis.

3.2.1. Carbon Footprint

Regarding the GHG emissions along the life cycle of H₂, Figure 2 shows the distribution of GWP for SMR, CG, EL, and biomass routes (SRBio, SREtOH, and BG) for H₂ production. For more information about the system boundaries and geography of the H₂ system, see Table A1.

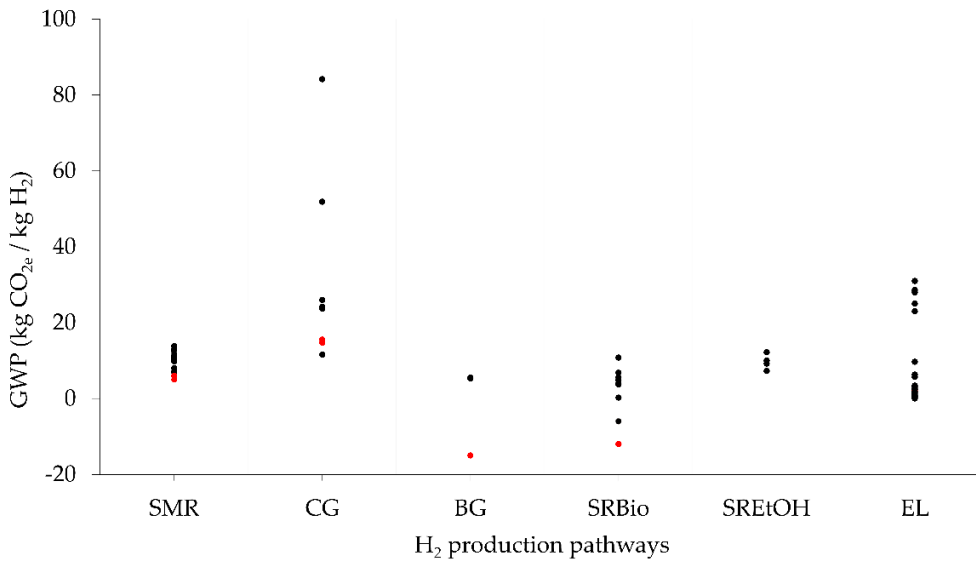


Figure 2 – GWP of H₂ production systems, mass relative²

Source: Own elaboration

² SMR: steam methane reforming; CG: coal gasification; SREtOH: steam reforming of ethanol; SRBio: steam reforming of biogas; BG: biomass gasification; EL: water electrolysis. Red points indicate technologies with CCS

In order to compare the GWP of H₂ systems with traditional fossil fuels, Figure 3 shows that H₂ can reduce GHG emissions when renewable energy is used or when CCS technologies are coupled with fossil-based H₂. However, depending on the electricity source used for feeding electrolysis systems, the GWP of those routes can be higher than traditional-based fossil fuels. The GWP ranges from 63 gCO_{2eq}/MJ of natural gas to 88 gCO_{2eq}/MJ of fossil diesel (which is represented by the grey bar in Figure 3), according to Raboni, Viotti and Capodaglio (2015). Routes based on biomass can deliver lower GHG emissions than fossil resources when H₂ is produced from waste.

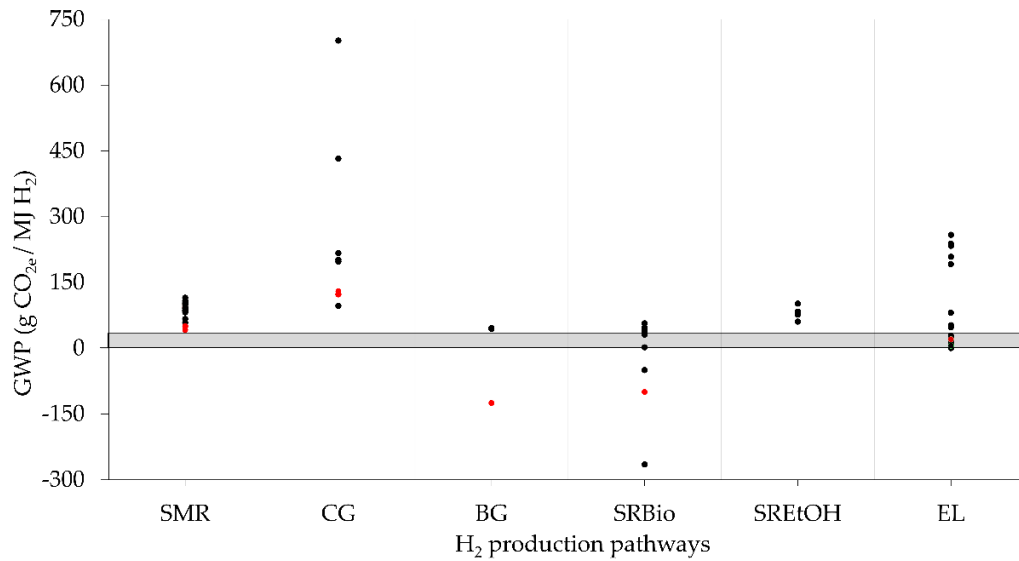


Figure 3 – GWP of H₂ production systems, energy parity³

Source: Own elaboration

SMR is often used as a benchmark for comparing other methods, as it is the conventional technique for H₂ production, and renewable alternatives provide a pathway to transitioning away from fossil fuels. According to the studies reviewed, the GWP of the SMR method averages 11.4 kg CO_{2eq}/kg H₂.

For fossil pathways, emissions from the H₂ production phase are a key contributor to the GWP observed for the SMR and CG. However, in Figure 4, it can be seen that pathways that employed CCS technologies, such as upstream processes, are the main contributors to GWP (Henriksen *et al.*, 2023; Liu; Liu, 2021).

For routes based on biomass, contribution analysis depends on the boundaries of LCA studies. Credits can be given for upstream processes, i.e., biomass growth and landfill gas recovery (Battista *et*

³ Red points indicate technologies with CCS

al., 2017; Hajjaji *et al.*, 2013). In the case of EL systems, upstream electricity generation drives the GWP contribution.

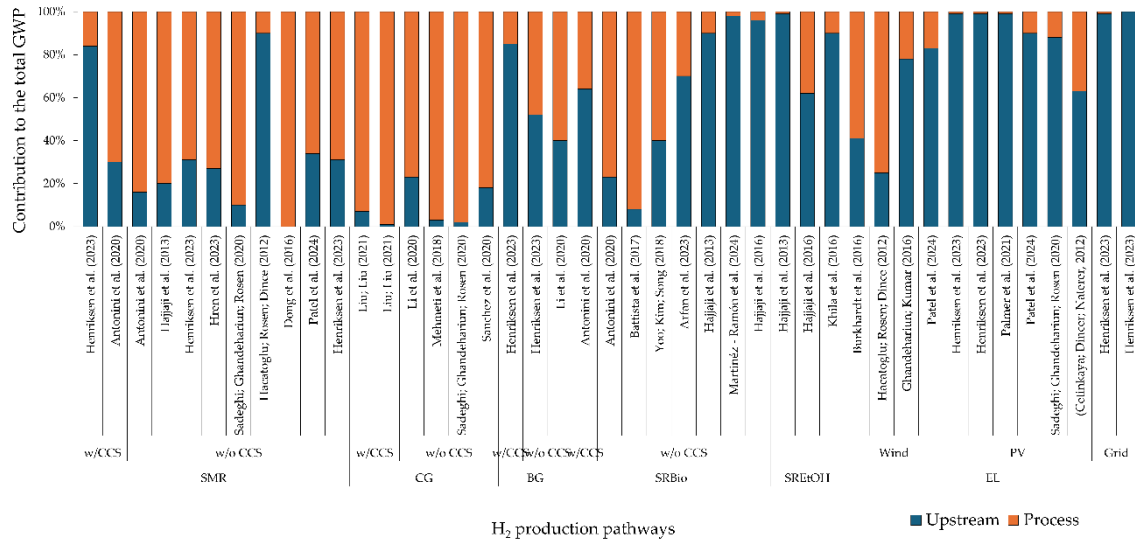


Figure 4 – Contribution analysis for GWP⁴

Source: Own elaboration

Valente, Iribarren and Dufour (2020) analyzed the GWP of SMR using the LCA approach, considering scenarios with efficiency improvements and a higher share of renewable energy in the electricity grid for 2030 and 2050. However, the study found that the GWP would remain around 10.0 kg CO₂e/kg H₂ by 2050. Similarly, Sadeghi, Ghandehariun and Rosen (2020) used LCA to estimate a GWP of 10.3 kg CO₂e/kg H₂, with 90% GHG emissions coming from natural gas consumption during operation, and only 1% attributed to the plant's construction and manufacturing.

In another study, Hren *et al.* (2023) estimated a GWP of 7.0 kg CO₂e/kg H₂ for the SMR method, noting operation phase contributed to 70% of total GHG emissions. A heat integration process was considered in reforming phase by the authors, which reduces overall natural consumption. They also pointed out that the compression stage could increase emissions by up to 0.64 kg CO₂e/kg H₂ for gaseous compression (up to 700 bar) and 3.0 kg CO₂e/kg H₂ liquefied.

Finally, Patel *et al.* (2024) reported a GWP of 12.4 kg CO₂e/kg H₂ for the SMR method, considering the extraction and transportation of natural gas by pipeline to the SMR facility, with the operation contributing around 66%, and natural gas transportation and extraction accounting for 25% of the GWP due to leaks considered by the authors.

Studies on CG pathways demonstrated to have the highest GWP values. However, technologies

⁴ H₂ production with CCS is referred to as “w/CCS”, and an H₂ system without CCS is referred to as “w/o CCS”

that apply CCS can reduce, significantly, GHG emissions. For instance, Li *et al.* (2020) reported a GWP of 52 kg CO₂e/kg H₂, with the operation phase being the largest contributor, accounting for about 60% of emissions. Similarly, Mehmeti *et al.* (2018) and Sadeghi, Ghandehariun and Rosen (2020) and Sanchez *et al.* (2020) noted that coal gasification phase could account for up to 90% of emissions.

In particular, CCS could be more beneficial for the CG method, as it has a higher proportion of CO₂ available for capture compared to SMR, potentially leading to a 75% reduction in emissions (Simons; Bauer, 2011).

The capture rate of direct emissions in H₂ production stage can reach values of 60% - 90% for CG process (Liu; Liu, 2021). The authors compared two pathways for H₂ production with CCS technology: deep and surface coal gasification (the distinction between deep coal and surface coal revolves around the methods of extraction and the geological conditions under which they are found). They found that GHG emissions can be reduced by half, reaching GWP values of 14 kg CO₂e/kg H₂.

For the processes based on biomass, GWP can vary from -32 up to 12 kg CO₂e/kg H₂ depending on the energy feedstock employed for H₂ generation as well as LCA boundaries and credits given for upstream processes. For instance, routes based on EtOH, the average GWP was estimated at 8.0 kg CO₂e/kg H₂.

Hajjaji *et al.* (2013) found a GWP of 9.2 kg CO₂e/kg H₂ for SREtOH from wheat grains, noting that 54% of the GWP came from wheat production because fertilizer application activities and 45% from the ethanol distillery due to the use of natural gas for heating purposes. Since animal feed is produced alongside ethanol, the authors expanded the system boundaries to offset the production of conventional animal feed.

Khila *et al.* (2016) reported a GWP of 7.26 kg CO₂e/kg H₂ for beet ethanol, with 51% of GHG emissions attributed to the electricity used by the plant and 38% to ethanol distillery. By contrast, Siddiqui and Dincer (2019) reported a GWP of 12.2 kg CO₂e/kg H₂ for SREtOH derived from corn under North American conditions.

On the other hand, technologies that use biogas for H₂ production via steam reforming can have GWP values ranging from -32.0 to 3.9 kg CO₂e/kg H₂. Wijayasekera *et al.* (2022) reported a negative GWP of -32 kg CO₂e/kg H₂. This negative value is attributed to the credit for biogas, as emissions that would have occurred if the waste had been sent to a landfill are offset.

Battista *et al.* (2017) found a GWP of 6.5 kg CO₂e/kg H₂ (0.6 kg CO₂e/Nm³ H₂) for SRBiogas from agro-industrial waste anaerobic digestion. The authors argued that this is the best method for biogas production due to its high CH₄/CO₂ ratio and the potential use of digestate as biofertilizer.

In a well-to-wheel assessment of H₂ production from landfill gas (LFG) in South Korea, Yoo, Kim and Song (2018) estimated a GWP of 3.9 kg CO₂e/kg H₂. The upstream process received credit since GHG emissions from flaring are offset when biogas is produced from LFG. The total credit amounts to 68.2 kg CO₂e/GJ H₂ linked to LFG recovery.

The negative of -4.8 kg CO₂e/kg H₂ produced from SRBio found by Antonini *et al.* (2020) is attributable to the net carbon balance considered if the digestate is applied as fertilizer and the CO₂ is sequestered in the soil. Martínez-Ramón *et al.* (2024) found a GWP of 10.8 kg CO₂e/kg H₂ for H₂ produced from biogas derived from anaerobic digestion of organic waste. They pointed out that biogas production is the main contributor to GWP result, accounting for more than 90% of total GWP, due to biogas leakage, set at 3% of generated biogas.

The EL process is recognized as a renewable and potential way of producing low-carbon H₂ (Chi; Yu, 2018). However, as previously mentioned, the source of electricity significantly impacts the GHG emissions throughout the lifecycle of electrolytic H₂. If electricity is sourced from the grid, it can result in high emissions, especially when a substantial share of fossil fuels is used for electricity generation.

Hren *et al.* (2023) found a GWP of 23.0 kg CO₂e/kg H₂ based on the average EU electricity mix in 2020, which included 44% fossil fuels. High GHG emissions was reported by Siddique and Dincer (Siddiqui; Dincer, 2019) whom found a GWP of 28.6 for US fossil grid mix (34% coal power, 32% natural gas and only a small percentage of renewable sources, 7%).

Mio *et al.* (2024) reported a GWP of 4.3 kg CO₂e/kg H₂ for alkaline electrolysis powered by PV energy and a fully renewable energy mix (45% hydro, 19% PV, and 15% wind). For electrolysis powered by PV and wind energy, most GHG emissions arise from the production of PV panels and wind turbines, accounts for 90% and 83%, respectively (Patel *et al.*, 2024).

3.2.2. Water Consumption

Electrochemical and thermochemical processes both use water for H₂ production as feedstock, for steam generation and cooling purposes. Several studies have analyzed the WC and WSF of H₂ production systems (Figure 5). Since different methods and indicators were used, the results are not directly comparable. The methods applied for each study are listed in Table A2.

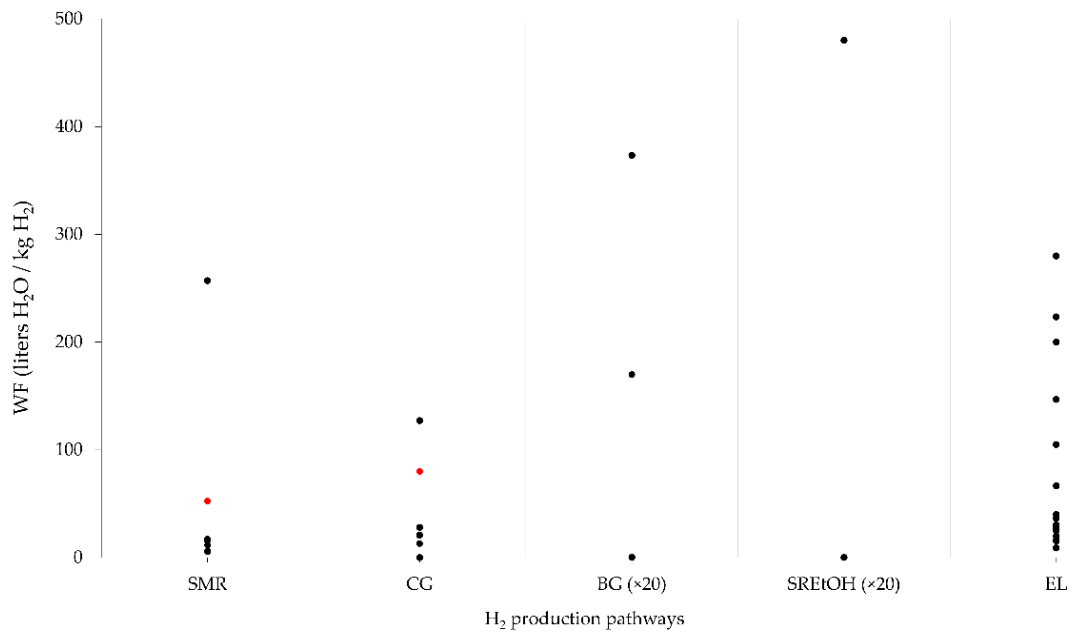


Figure 5 – WC of H₂ production systems⁵

Source: Own elaboration

For processes that rely on biomass for energy, most of the water use occurs during the growth or production of biomass (Cui *et al.*, 2021; Henriksen *et al.*, 2023; Olaitan; Bertagni; Porporato, 2024).

The EL method uses water directly to split the water molecules into H₂ and also for cooling. The source of electricity powering the electrolyzer has a significant impact on the water use for this method. Processes using PV and wind energy consume less water compared to those using grid electricity (Henriksen *et al.*, 2023; Mehmeti *et al.*, 2018; Shi; Liao; Li, 2020).

For PV and wind systems, most of the water is used in manufacturing equipment (Figure 6). In the case of biomass routes, WC is influenced by water consumption in feedstock crop cultivation. For fossil fuels pathways, WC relies on steam generation, and water consumed in natural gas and coal processing.

⁵ SMR: steam methane reforming; CG: coal gasification; BIO (SREtOH, SRBiogas, biogas gasification); EL: water electrolysis. Red points indicate studies that include blue, green, and grey water.

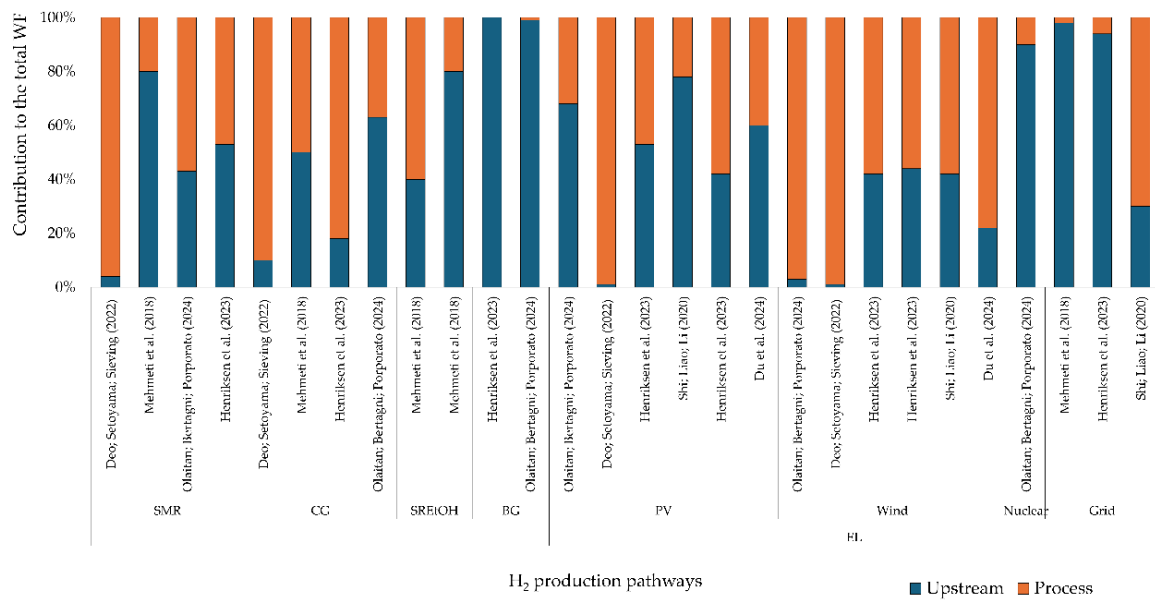


Figure 6 – Contribution analysis for WC

Source: Own elaboration

Deo, Setoyama and Sieving (2022) estimated the WC over the life cycle of seven H₂ production routes. They found that renewable routes, such as EL powered by wind and PV energy, consume less water (about 25%) than conventional routes like CG and SMR.

Cui *et al.* (2021) investigated the WC associated with H₂ production from biomass and coal. They found that the WC for the wheat straw-based route reached 9,400 L H₂O/kg H₂ over its life cycle, which is much higher than fossil fuel route, which consumes only 130 L H₂O/kg H₂. They highlighted that water use for biomass cultivation accounts for around 99% of the total WC, whereas only 4.15% comes from coal production. The authors considered both green and blue water essential for the agricultural phase of biomass, along with the indirect WC from fertilizers, electricity, and fuels. They emphasized that improving fertilizer application efficiency and soil fertility could significantly reduce WC during the agricultural phase. In coal-based H₂ production, WC is mainly driven by electricity usage, which accounts for more than 50% of the total indirect water consumption.

Shi, Liao and Li (2020) found a WC of 130.0, 40.0, and 20.0 L H₂O/kg H₂ for electrolysis powered by the Australian grid, PV, and wind systems, respectively. WC during the life cycle of PV and wind systems is mainly attributed to equipment production. By applying a WSF index, the same work estimated a WSF due to H₂ production in 3,000 L H₂O/kg H₂; 1000 and 500 for Australian grid mix, PV and wind electrolysis, respectively.

A study conducted by Mehmeti *et al.* (2018) quantified the WSF using the AWARE indicator found out a key tradeoff between WSF and GWP: routes with a high WSF impact generally tended to have a lower GWP. In terms of WC, they found that the WSF followed the same pattern as the WC.

They concluded that water scarcity is strongly influenced by electricity source, emphasizing the importance of combining technologies for both fuel and electricity production when assessing the water scarcity index.

A LCA analysis of eleven H₂ production pathways was carried out by Henriksen *et al.* (2023). It was estimated that WC ranged from 7 – 55 L H₂O/kg H₂ for fossil resource-based routes, and from 530 – 3,400 L H₂O/kg H₂ for biomass-based routes. BG with CCS technology showed the highest WC among the pathways analyzed due to water consumption for irrigation purposes. Their analysis considered only surface and groundwater consumption, excluding the green (or rain) water used in biomass cultivation routes. They also pointed out that it's important to note that although the cooling system operates as a closed loop, make-up water is still necessary to compensate for losses, such as blowdown losses and evaporation from cooling towers. Thus, the make-up water flow aligns with the calculated water consumption.

In EL processes, the electricity source is crucial for accurately estimating both GWP and WC. Olaitan, Bertagni and Porporato (2024) estimated the WC of EL powered by renewable energy compared to fossil resources, using the Water Footprint Network (Hoekstra *et al.*, 2012). They comprehensively evaluated the blue, grey and green water used for generating the primary energy resource, as well as water needed for process and operational uses (including feedstock and cooling water). For biomass-based routes, the WC could rise as high as 7,000 L H₂O/kg H₂ due to the inclusion of green water. Their findings showed that, while the WC can vary significantly, those using renewable resources (wind, PV) consistently demonstrated a lower WC compared to H₂ produced from SMR and CGR, even when carbon capture and storage were applied.

In the same way, by considering blue (irrigation) and green (precipitation) water needs for biomass crop cultivation Cui *et al.* (2021) estimated high WC for H₂ derived from wheat gasification. Values of WC can reach 9,300 L H₂O/ kg H₂ when electricity required for pyrolysis of biomass (BP) is derived from hydroelectricity. In general, the authors found that biomass cultivation phase is the large consumer of water in H₂ production.

The WC for SREtOH under Brazilian conditions was estimated in 9,600 L H₂O/kg H₂ for H₂ produced from sugarcane ethanol reforming (De Souza *et al.*, 2021). Most of the water consumption is associated with green water consumed at sugarcane crop cultivation. The same study employed WFA for estimating WC of SMR. It was found a WC of 257 L H₂O/kg H₂ which is associated with H₂ flow and exhaust gases.

Water availability issues can be a limiting factor for H₂ production since it is expected that about 40% of the production capacity for low-carbon electrolytic H₂ will be located in regions facing water scarcity (IEA, 2024b). However, a study by Tonelli *et al.* (Tonelli *et al.*, 2023) concluded that the water required for a hypothetical volume of green H₂ production (400 Mt/year by 2050) would account for less than 3% of total water consumption for agriculture, industry, and municipalities.

Even though several studies have assessed water consumption and availability throughout the H₂ life cycle, a recent study conducted by the World Economic Forum (WEF, 2022) demonstrated that only nine countries (out of the 135 evaluated) would need to increase their freshwater extraction by more than 10% to support an electrolytic H₂ energy system.

3.2.3. Energy Performance

Multiple studies (Figure 7) have highlighted the substantial use of fossil resources in renewable H₂ systems throughout their life cycle, indicating that even green H₂ production relies on fossil fuels to some extent (Cvetković *et al.*, 2021; Hajjaji *et al.*, 2016b; Mio *et al.*, 2024; Tripathi; Subramanian, 2022; Wijayasekera *et al.*, 2022). As a result, assessing the performance of the energy system has become crucial, with the goal of reducing dependence on fossil fuels while improving energy delivery.

As pointed out earlier, the energy indicator (EI) was estimated as the ratio between the lower heating value (LHV) of H₂ and the fossil energy consumption, measured by the Cumulative Energy Demand (CED), throughout the life cycle of the H₂ production systems. For more information on the CED estimation, see Table A3.

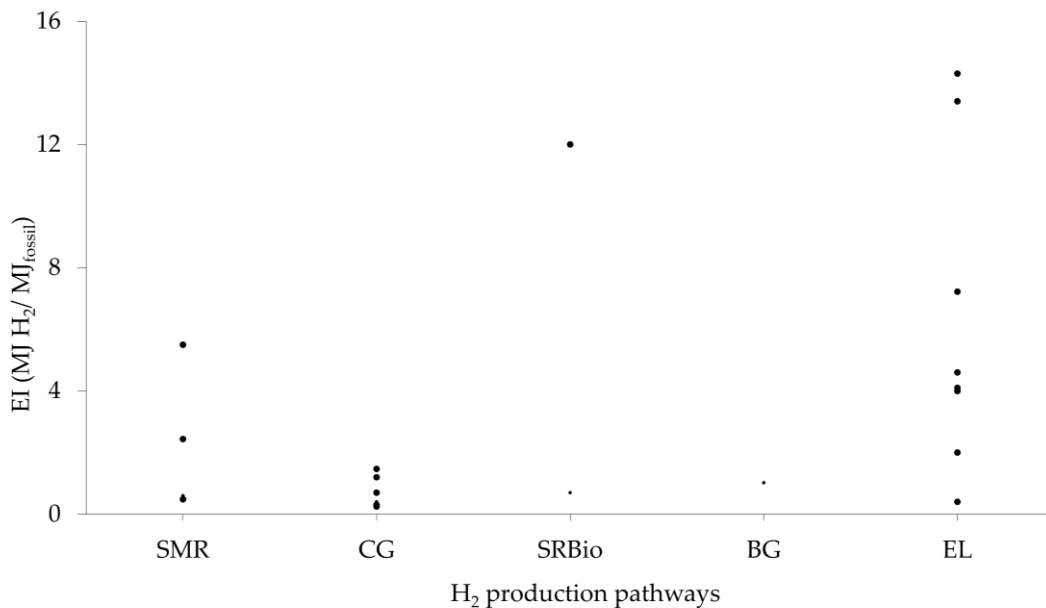


Figure 7 – Energy performance of H₂ production systems⁶

Source: Own elaboration

The main goal of an energy system is to convert energy efficiently, and one way to measure this

⁶ SMR: steam methane reforming; CG: coal gasification; Bio (SREtOH, SRBiogas, and biogas gasification); EL: water electrolysis. The energy indicator (EI) was estimated by the authors based on a low heat value (LHV) of H₂ ($EI = LHV_{H_2} / CED_{fossil}$)

efficiency is through the "Cumulative Energy Demand" (CED), which measures the energy consumed by a production system during its lifecycle. Energy systems face a twofold challenge: they must reduce GHG emissions while increasing energy output. In this context, assessing the energy performance of H₂ systems is essential.

Several studies that have evaluated the efficiency of H₂ production systems using the LCA approach demonstrated that AEL systems consume higher fossil energy in upstream process, mainly for electricity generation and energy consumed for equipment manufacturing (Burkhardt *et al.*, 2016; Dufour *et al.*, 2012; Palmer *et al.*, 2021). In the case of biomass routes, studies have shown that upstream process associated biomass crop cultivation have great influence on energy consumed throughout life cycle of H₂ systems (Cvetković *et al.*, 2021; Hajjaji *et al.*, 2016a; Li *et al.*, 2020).

A study conducted by Liu *et al.* (2023) estimated fossil energy consumption for deep CG, and SMR. They found CG and SMR consumed 450 MJ/kg H₂ (EI 0.27) and 250 MJ/kg H₂ (EI 0.48), respectively. The high dependence on fossil resources reflects the reduction of EI or the renewability of H₂.

An EI for EL using PV and grid energy (100% renewable), as well as for SMR was estimated in 13.4, 14.3, and 5.48 for PV EL, grid energy, and the SMR process, respectively (Mio *et al.*, 2024). According to the authors, the higher EI for AEL compared to the SMR process is due to the high EROI of the fuels in the energy mix used for the AEL system.

A CED of 163.7 MJ/kg H₂ (EI 0.7) was found for H₂ production from biogas derived from the anaerobic digestion of cattle manure and corn silage (with digestate applied to the field). This value is lower than the estimated 185.1 MJ/kg H₂ (EI 0.65) for the SMR route, but much higher than the CED (8.8 - 54.5 MJ/kg H₂) reported for electrolysis systems (Cvetković *et al.*, 2021). The authors concluded that, from an energy perspective, the biogas H₂ system is unsustainable due to the high natural gas consumption required to achieve the necessary temperature for the reforming process (with 20% of the total energy coming from biomethane and 80% from natural gas).

A high fossil energy consumption was examined by Burkhardt *et al.* (2016) who found a total CED (including construction, operation and decommissioning) of 34.3 MJ/kg H₂ (EI 4.4 for wind energy-based electrolysis operation), with 82 % of the CED attributed to fossil energy use along life cycle of the H₂ system. Kinect energy of wind was not included in CED estimation.

An EI of 4.6 for H₂ produced through AEL powered by PV energy was reported by Palmer *et al.* (2021). They found that the PV modules have the largest impact, followed by the balance of system components (frames, hardware). Desalination facility has a minimal contribution in terms of built-in and consumed energy. It is important to note that the system's lifespan is a key factor for this indicator – plants with shorter lifespans tend to yield a lower EI. The cited paper considered the solar energy for CED estimation.

Dufour *et al.* (2012) evaluated fossil resource consumption through CED for electrolytic routes

powered by PV, wind, and grid energy (with only 14% of the energy being renewable). For wind power, a CED of 28 MJ/kg H₂ (EI 4.3) was reported; 62 (EI 1.9) for PV; and 341 (EI 0.4) for grid-based electrolysis. These figures clearly show that the grid-based system, with its high reliance on fossil energy, constitutes the most unfeasible scenario due to the significant presence of non-renewable resources in the electricity mix.

A comprehensive study regarding EI was conducted by Mio *et al.* (2023) who also included the energy input required for system construction and maintenance, beyond its operation. In general, they found that electrolysis-based methods (particularly those combining PV energy with a 100% grid energy source) exhibit a 66% superior EI compared to SMR technology. This is largely due to the higher EI values of renewable energy resources compared to natural gas, a key input in the H₂ production process via SMR. It is important to note that renewable solar energy was included in their estimation.

Battista *et al.* (2017) found an EI of 8.4 (4.5 MJ/Nm³ H₂) for SRBiogas from agro-industrial waste anaerobic digestion. Their contribution analysis showed that biogas reforming and partial oxidations have the most significant contribution in energy consumption (more than 85%) followed by biogas purification process. Li *et al.* (Li *et al.*, 2020) estimated a fossil consumption of 117 MJ/kg H₂ (EI 1.02) for BG pathway. It was reported that straw production and straw transportation stage contribute to 50% of total energy consumption.

In a cradle-to-grave analysis, Hajjaji *et al.* (2016b) assessed the environmental impacts of H₂ derived from an anaerobic digestion plant (which uses farm waste, cheese whey, maize silage and fodder beet for biogas production). By crediting the digestate application in the field (displacing mineral fertilizers), the authors estimated a CED of 4.97 MJ/kg H₂ (EI = 26) for producing 1.0 kg of H₂ in which 84% is non-renewable energy. Without credits given for digestate use as fertilizer and the credits for the recycling of plant equipment, the EI is estimated to be 12 MJ H₂/MJ fossil energy.

Despite the variety of resources and technologies for H₂ production, its use faces significant energy inefficiencies throughout the supply chain. When it is used in fuel cells, only 29% of the total energy invested is converted into useful energy (Brandon; Kurban, 2017). For applications that burn H₂, the overall efficiency is much lower, with considerable energy losses occurring during transportation and distribution as well as in other stages of the supply chain. H₂ burned in internal combustion engines (gas turbines) has low overall efficiency – around 21 to 26% (Brandon; Kurban, 2017). This low efficiency is due to hydrogen's low volumetric energy density.

Additionally, the infrastructure required for storing and transporting H₂ can lead to significant energy consumption. The main methods for storing and transporting H₂ involve both its gaseous and liquid states. Compressing H₂ to pressures ranging from 300 to 700 bar requires substantial energy and results in a gravimetric density of less than 40 kg/m³. The energy spent on the compression process can account for 13–18% of the LHV of the stored H₂, exceeding 2.21 kWh/kg H₂. On the other hand, liquefying H₂ requires energy for both compression and cooling to 20.15 K, which can consume up to

45% of the LHV of H₂, though it achieves a gravimetric density of 70.8 kg/m³ (Aba; Sauer; Amado, 2024; Castro *et al.*, 2023). In this sense, evaluating energy consumption across the entire life cycle of H₂ systems is essential.

3.3. Green Ammonia as alternative for Hydrogen use

In 2018, NH₃ synthesis accounted for approximately 42% of global H₂ consumption, while the oil refining industry represented the largest share, consuming about 52% of the total 72 Mt of H₂ produced that year (IEA, 2019).

As H₂, ammonia (NH₃) can be synthesized either from RES or fossil fuels (Valera-Medina; Banares-Alcantara, 2020). Currently, NH₃ production relies on fossil fuel, mainly on natural gas reforming (72%) and coal gasification (26%) (Djire *et al.*, 2025; IEA, 2021). Depending on the energy source for NH₃ synthesis, it can be labeled as gray NH₃ (based steam reforming of natural gas - SMR); brown NH₃ (derived from coal); blue NH₃ (coal or natural gas integrated with carbon capture and storage technology); and green NH₃ (produced using renewable sources) (Fernandes, 2022; Gezerman, 2022; Jabarivelisdeh *et al.*, 2022).

Low-carbon NH₃ has been pointed out as an important chemical building block for the decarbonization of the energy, industry and transport sectors (Fernandez *et al.*, 2024). Mostly of NH₃ applications are concentrated in fertilizers industry which consumed 70% of global NH₃ production in 2020 (Bartels, 2008; IEA, 2021; Pawar *et al.*, 2021). Globally, urea fertilizer production consumed 55% of NH₃ produced in 2020 (Akbari; Oyedun; Kumar, 2018; IEA, 2021).

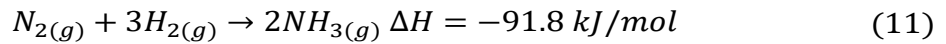
Refrigeration, textiles, metallurgical industries and water treatment also consumes NH₃ (Bora *et al.*, 2024; Gezerman, 2022; Smith; Hill; Torrente-Murciano, 2020). In fact, the application of NH₃ in agriculture has been a key determinant of improved productivity in food production (Bora *et al.*, 2024). The economic and population growth expects to increase NH₃ demand will up to 40% in 2050 compared to a demand of 152 Mt in 2020 (IEA, 2021).

Applications of NH₃, beyond its use in agriculture, are the possibility of converting it into electricity through electrochemical cells or by combustion. Even though NH₃ is safer to transport than H₂, due to its the properties, such as its high ignition temperature and low laminar burning velocity, challenges arise for its combustion with high efficiency (Nguyen *et al.*, 2025) which can achieve efficiencies of only 40% (Sánchez *et al.*, 2021). In addition, NH₃ combustion emits N₂O, which has a significant impact on climate change, air pollution and soil quality (Gezerman, 2022; Nguyen *et al.*, 2025). Also, there are still concerns about the hazards associated with NH₃ like its flammability, toxicity and its potential to causes eye damages and the long lasting effects with aquatic life (Bora *et al.*, 2024).

Additionally, NH₃ has been seen as a promising energy vector (Pawar *et al.*, 2021) and as a suitable marine fuel (Bartels, 2008; Cheliotis *et al.*, 2021). Applications of green NH₃ in the maritime freight sector are being discussed, given the International Maritime Organization's commitment to

reduce emissions by 50% by 2050 compared to 2008 levels (IEA, 2023). It is projected that NH₃ will account for 44% of marine shipping fuel by 2050 (Garvey *et al.*, 2025).

In general, NH₃ synthesis can be characterized into four steps: syngas production, which is a mixture of CO₂, CO and H₂; water gas shift reaction which is used to improve H₂ concentration in syngas; followed to syngas purification in order to remove acid gas and increase H₂ purity and the last stage is the Haber-Bosh (H-B) process that combines N₂ and H₂ for NH₃ reaction (Cesaro, 2022; Fasihi *et al.*, 2021). The H-B process consists of the combination of H₂ and N₂ for NH₃ production in an exothermic reaction (Djire *et al.*, 2025):



Energy integration and optimization of operational processes have decreased energy consumption by 30% compared to the initial process, however, besides the improvement in energy efficiency, GHG emissions are still significantly (Smith; Hill; Torrente-Murciano, 2020).

A promise alternative for the conventional natural gas based-NH₃ is the use of RES for producing green NH₃ which can result in lower GHG emissions (Djire *et al.*, 2025; Smith; Hill; Torrente-Murciano, 2020). H₂ and N₂ are produced through RES which is used for powering water electrolysis and the air separation unit (ASU) as well as the H-B unit (Bora *et al.*, 2024). Also, CCS technologies can be an alternative in near and medium term for decarbonization of conventional NH₃ production (Fernandez *et al.*, 2024).

Even though green NH₃ from electrolytic H₂ is not a new commodity - with production technology dating back to the 1920s - global concerns about environmental issues and the persistent reliance on fossil fuels have reignited the debate on green NH₃ production (Akbari; Oyedun; Kumar, 2018, 2018; Smith; Hill; Torrente-Murciano, 2020; Tunå; Hulteberg; Ahlgren, 2014). Furthermore, the decline in the cost of RES, the reduction in electrolyzer manufacturing costs have all driven interest in green NH₃ commodity (Rouwenhorst; Travis; Lefferts, 2022).

NH₃ production consumes around 2.0% of energy globally and accounts for 1.2 - 2.0% of total CO₂ emissions (Al-Mamoori *et al.*, 2017; Bora *et al.*, 2024; Fernandes, 2022; Smith; Hill; Torrente-Murciano, 2020). This is explained by the reliance on fossil fuel for NH₃ synthesis (Smith; Hill; Torrente-Murciano, 2020). Table 2 below compares the GHG emissions of NH₃ pathways:

Table 2 – GHG emissions of NH₃⁷

Feedstock	Technology	Average GHG emissions (t CO ₂ e/t NH ₃)
Natural Gas	Steam Reforming	2.1
Heavy fuel oil	Gasification	3.3
Coal	Gasification	4.6
Electricity	Electrolysis	0.3 – 0.9

Source: Own elaboration

Around one-third of CO₂ emissions are attributed to natural gas burning and two-thirds of CO₂ emissions are attributed to feedstock conversion (Gezerman, 2022; Jabarivelisdeh *et al.*, 2022; Mersch *et al.*, 2024; Smith; Hill; Torrente-Murciano, 2020). In the case of NH₃ derived from coal, 25% of emissions are associated with fuel combustion and the remaining, the usage of coal as feedstock. In this sense, looking for alternatives for H₂ production is important due to the opportunity to decrease GHG emissions of NH₃ synthesis (Gezerman, 2022).

Green NH₃, produced from electrolytic systems powered with RES, has the potential to reduce energy consumption by up to 50% and CO₂ emissions by 78% compared to conventional production routes (Smith; Hill; Torrente-Murciano, 2020). For green NH₃, emissions can range from 0.3 up to 0.9 kg CO₂e/kg NH₃ for H-B powered with PV and wind electricity, respectively (Vinardell *et al.*, 2023).

In this regard, electrolytic or green NH₃ can significantly reduce carbon emissions compared to the conventional process (Mersch *et al.*, 2024) and the same time, reduce GHG associated with the applications of NH₃ such as in agriculture, transport and energy sectors (Bora *et al.*, 2024).

Cost of NH₃ is strongly associated with natural gas prices. The cost varied between 400 USD/t NH₃ to 1,600 USD/t NH₃ in 2022 and 2023, respectively, due to natural gas prices fluctuating (Fernandez *et al.*, 2024). In the case of electrolytic NH₃, its cost is influenced by electricity price which results in higher cost for H₂ production (Arnaiz Del Pozo; Cloete, 2022). Green NH₃ cost can range of USD 720 – USD 1,400 (2020) per ton and falling to USD 310 – 610 in 2050 (IRENA; AEA, 2022).

Electrolytic NH₃ synthesis plants can run in conjunction with dispatchable low-carbon energy sources or variable renewable energy. However, the H-B process requires stable demand for H₂, which may pose a challenge for dedicated intermittent systems (IEA, 2021). Nonetheless, the high electricity consumption for green NH₃ production compared to natural gas NH₃ (12 MWh/t NH₃ and 8 MWh/t NH₃) has become a constraining factor for enhance green NH₃ synthesis (Gezerman, 2022).

Also, for electrolytic NH₃, the scaling up of electrolysis plants can become an issue to the

⁷ From (Jabarivelisdeh *et al.*, 2022; Vinardell *et al.*, 2023)

development of such commodity (Djire *et al.*, 2025). Large fossil NH_3 plants can produce between 1,000 to 1,500 t NH_3 /day; however, some facilities can deliver up to 3,000 tons per day (Jabarivelisdeh *et al.*, 2022).

This high level of production capacity cannot be achieved for electrolytic NH_3 using Proton Exchange Membrane (PEM) electrolyzer, which can deliver only 10 t H_2 /day which is the volume necessary for producing only 56 t NH_3 /day (Gezerman, 2022). However, there are planned plants of green NH_3 capable of delivering up to 1.2 Mt NH_3 /yearly and electrolyzer capacity of 15,000 MW (Salmon; Bañares-Alcántara, 2021).

On the other hand, small and decentralized green NH_3 production with individual capacity between 100 - 300 tons per year can improve fertilizer accessibility, especially in regions with logistic barriers helping to reduce transport cost, GHG emissions associated with fertilizer supply chain as well as avoiding fertilized market prices fluctuations (Garvey *et al.*, 2025). IFA (2024) projects project that green NH_3 will account for 15% of global production in 2028.

In contrast to the worldwide, Brazil's GHG emissions differ from global patterns, being mainly concentrated in land use change (53%) and agriculture (24%), while the energy sector accounted for only 16% in 2022 (Climate Observatory, 2025). In 2021, agricultural activities – including livestock, fertilizer use, waste management, irrigated rice cultivation, and residue burning – were responsible for about 25% of national emissions (Bieluczyk *et al.*, 2024). Brazil was the world's fourth-largest fertilizer consumer in 2020, accounting for 8% of global demand, primarily using potassium (38%), phosphorus (33%), and nitrogen (29%) fertilizers, with soybean, maize, and sugarcane crops together consuming 72% of total fertilizer use in 2022 (Almeida; Volotão, 2020; Argenta *et al.*, 2023; Brasil, 2023).

The high dependence on external input negatively impacts the agribusiness trade balance (Figure 8) and leaves the country vulnerable to geopolitical uncertainties and fluctuations in exchange rates and prices (Argenta *et al.*, 2023). Additionally, logistics are a key point for cost composition of fertilizers production. In the state that consumes the most fertilizers, Mato Grosso, there is no local production of this input, nor is there adequate transportation infrastructure (Almeida; Volotão, 2020). Domestic industry is not able to accomplish the increasing demand for fertilizer, thus resulting in high dependence for imports (Castro; Silva; Gilio, 2021).

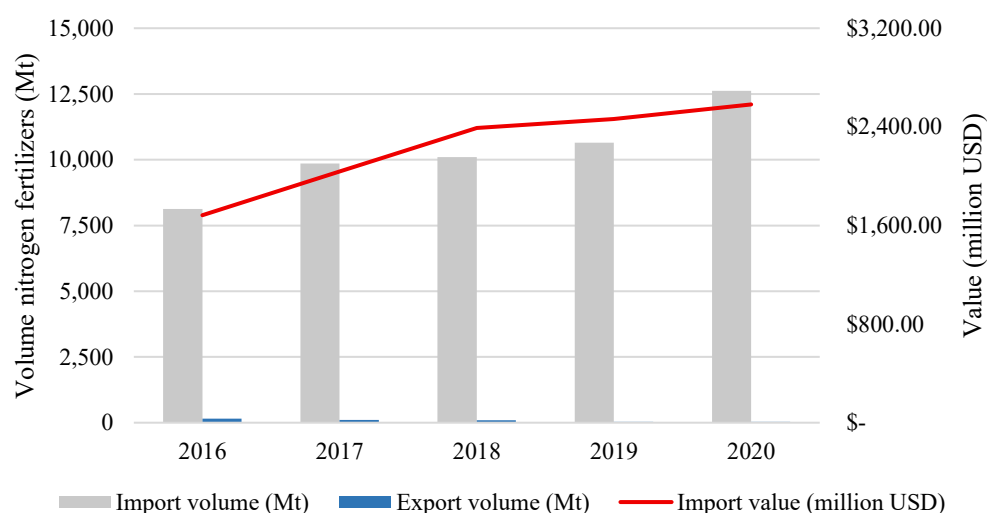


Figure 8 – Nitrogen fertilizer market⁸

Source: (Brasil, 2021)

In 2022, 85% of total Brazilian fertilizer consumption was imported (Argenta *et al.*, 2023; Brasil, 2023). Nitrogen fertilizers represented 35% of total volume of fertilizers imports (Almeida; Volotão, 2020). Between 2016 and 2021 (Figure 9), domestic nitrogen fertilizer production capacity decreased from 3 Mt to less than 1 Mt; during the same period, imports increased from 8 million tons to 12 Mt (Argenta *et al.*, 2023).

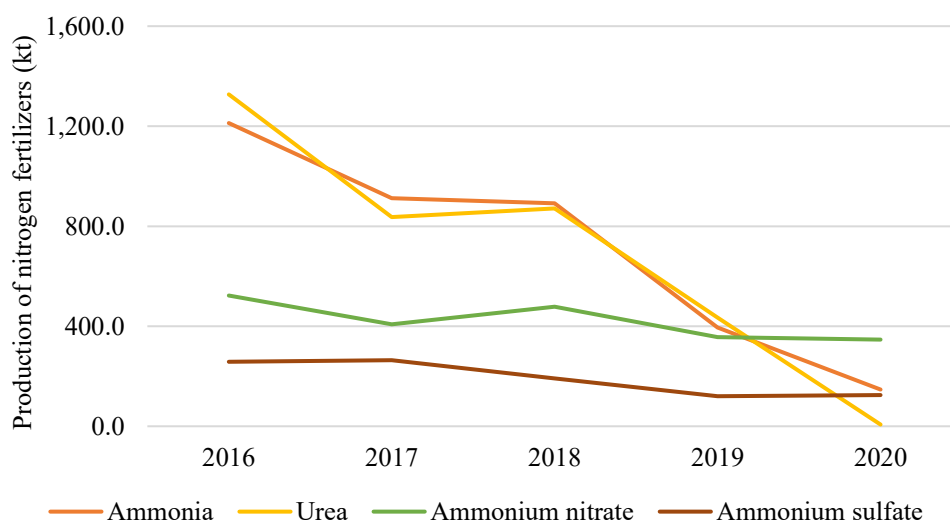


Figure 9 – Domestic production of nitrogen fertilizers⁹

Source: (Brasil, 2021)

⁸ Values based on (Brasil, 2021)

⁹ Values based on (Brasil, 2021)

It is projected that demand for nitrogen fertilizer will be double in 2050 in Brazil (Brasil, 2023). As global landscape, the small fraction of NH_3 produced in Brazil is derived from natural gas reforming (Barros Souza Riedel *et al.*, 2024; Brasil, 2023).

In 2024, the agribusiness sector accounted for 23.2% of Brazil's GDP (CNA, 2025b) and employed 28.2 million people, representing 26.02% of total employment in the same year (CNA, 2025a). Nearly half of Brazil's total exports in 2019 originated from the agribusiness sector (CNA, 2025b), highlighting its critical importance to the national economy. However, as previously noted, this sector is also responsible for the largest share of GHG emissions in the country. In this context, reducing dependence on imported fertilizers and increasing the use of renewable inputs could not only help close the domestic production gap (Caligaris *et al.*, 2022) but also mitigate GHG emissions associated with agricultural activities.

4 DATA AND METHODOLOGY

In alignment with the objectives of this study, the subsequent sections outline: (i) the assumptions underlying the life cycle assessment (LCA) of H₂ production pathways, (ii) assumptions regarding H₂ utilization for NH₃ synthesis; and (iii) the assumptions for socioeconomic analysis, by employing Input-Output (I-O) approach, pertinent to NH₃ production within the Brazilian context.

4.1.1. Scope and Boundaries

The goal of this study is to evaluate the environmental performance of ten H₂ production pathways in terms of GHG emissions, WSF, and primary fossil energy consumption (FER), as well as to explore potential *trade-offs* among these indicators. The selected H₂ production pathways are shown in Figure 1 and include two technologies: Steam Reforming (SR) and Alkaline Electrolysis (AEL). The following pathways were selected for H₂ production: P1- steam reforming of natural gas, P2 – steam reforming of corn ethanol, P3 – steam reforming of sugarcane ethanol, P4 – steam reforming of biogas, P5 – electrolysis based on the Brazilian Grid, P6 – electrolysis based on Brazilian marginal Grid, P7 – electrolysis based on PV electricity (*on-grid*), P8 – electrolysis based on PV coupled with battery (*off-grid*), P9 – electrolysis based on wind electricity (*on-grid*) and P10 – electrolysis based on wind electricity coupled with battery (*off-grid*).

An attributional approach was adopted in this study. This approach characterizes the production system by using average data to represent the existing conditions of the system under analysis. In this context, the allocation of environmental burdens among co-products is considered a consistent and appropriate procedure within a cause-oriented attributional LCA framework (Capaz, 2021). Thus, the co-products produced in the intermediary processes were handled by energy allocation (ANP, 2024), while the entire environmental burden was allocated to H₂ production.

The functional unit (FU) was defined as 1.0 kg of H₂ produced at 200 bar, as recommended by Lozanovski et al. (2011). The energy required for H₂ compression was estimated using a multi-stage compression system (Khan *et al.*, 2021). A cradle-to-gate analysis was assumed, thus, environmental impacts from the manufacturing and construction phases were included. Due to the high variability and uncertainty associated with end-of-life assessment, this phase was excluded from the analysis (Gandiglio *et al.*, 2022). Moreover, as several components of the renewable scenarios may be reused or recycled, this exclusion can be considered a conservative assumption.

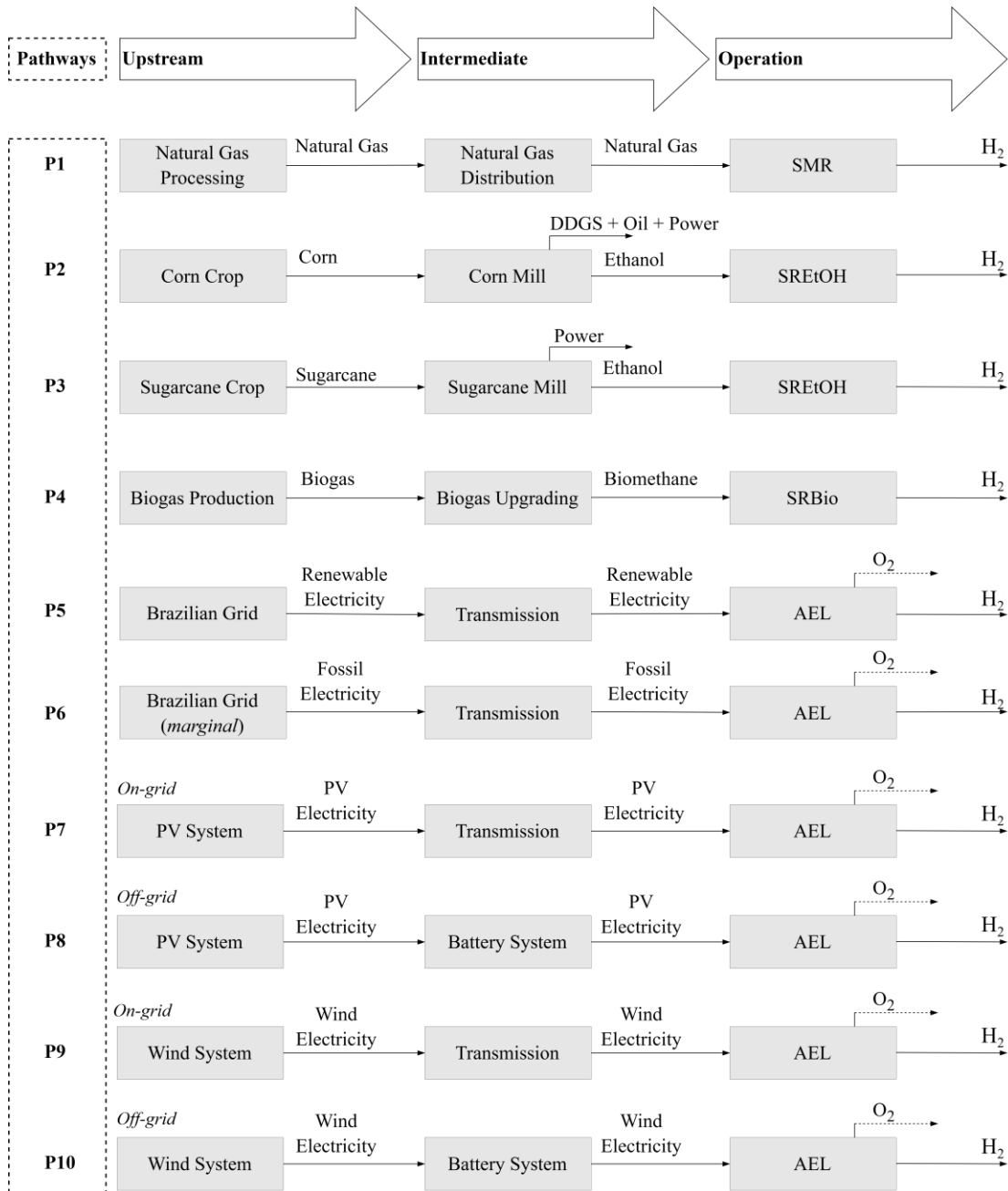


Figure 10 – System boundaries for H₂ production

P1 – steam reforming of natural gas (SMR), P2 – steam reforming of corn ethanol (SREtOH Corn), P3 – steam reforming of sugarcane ethanol (SREtOH Sugarcane), P4 – steam reforming of biogas (SRBio); P5 – electrolysis powered by the Brazilian Grid (AEL BR Grid), P6 – electrolysis powered by the Brazilian marginal Grid (AEL BR marginal), P7 – electrolysis powered by PV electricity on-grid (AEL PV on-grid), P8 – electrolysis powered by PV with battery storage (AEL PV off-grid), P9 – electrolysis powered by wind electricity (AEL wind on-grid) and P10 – electrolysis powered by wind electricity with battery storage (AEL wind off-grid)

To improve the accuracy of the results and reduce uncertainties in the LCA inventories and outcomes, regionalized data specific to Brazil was used. Regional variability in water availability, electricity supply, and infrastructure conditions shapes the environmental and operational feasibility of H₂ systems, reinforcing the need for holistic evaluations that account for contextual constraints and avoid shifting burdens across resource domains (Elaouzy; El Fadar, 2024; Silva; Capaz, 2025).

Background processes, such as those related to fertilizers, fuels, and power production, were sourced from the EcoInvent v3.9 database (Ecoinvent, 2023), with specific adjustments to the Brazilian context, *e.g.*, all diesel used in vehicles in Brazil contains a 14% biodiesel blend (CNPE, 2023). For more details see the Supplementary Information material.

SimaPro v9.5 software was used to model the H₂ LCA systems and assess the fossil energy ratio (FER) and global warming potential (GWP) midpoint impact categories (SimaPro, 2024). Due to the lack of regionalized AWARE factors in SimaPro, water scarcity footprint (WSF) was assessed using Microsoft Excel. The SMR process was chosen as the baseline, given that it accounts for 95% of Brazil's H₂ production (Santana *et al.*, 2023)

4.1.2. Pathways Description

The following sections describe the AEL and SR processes considered and analyzed in this study. The main assumptions for each H₂ pathway are described in Table 3.

Table 3 – Characteristics of H₂ pathways

Parameter	SR	SREtOH	AEL	Unit
Annual hours operation	7,900	7,580	8,300	h/year
System lifetime	20	20	20	years
Pressure delivery, in original reference	24	22	33	bar
Production rate H ₂	5,600	65.0	118.0	kg H ₂ /h
Electricity				
Process	0.31	0.49	-	kWh/kg H ₂
Compression (up to 200 bar)	1.17	1.22	0.97	kWh/kg H ₂
Utility				
Natural Gas	0.42	-	-	m ³ /kg H ₂
Biomethane	0.45	-	-	m ³ /kg H ₂
Ethanol	-	1.15	-	L/kg H ₂
Feedstock				
Ethanol	-	7.14	-	L/kg H ₂
Electricity	-	-	50.0	kWh/kg H ₂
Water	-	-	10.9	L H ₂ O/kg H ₂
Natural Gas	3.82	-	-	m ³ /kg H ₂
Biomethane	4.10	-	-	m ³ /kg H ₂
Water for cooling	15.8	17.9	4.6	L H ₂ O/kg H ₂
References	Spath & Mann (2001)	NREL (2018)	Koj et al., (2017) and NREL (2018)	

Water Electrolysis

H₂ was initially produced through water electrolysis process (Şahin, 2024). However, the high energy and economic costs of this method have kept it from being employed more widely, and today, electrolytic H₂ accounts for only 4% of global production (Ji; Wang, 2021). Water electrolysis involves splitting water into H₂ and O₂ by applying a current to an electrolyzer (Dufour *et al.*, 2012). The mature alkaline electrolysis (AEL) uses an alkaline solution, such as KOH or NaOH (typically 25% by volume), with the anode and cathode immersed and separated by a porous diaphragm that allows for the separation of H₂ and O₂ (Aydin; Dincer, 2022).

This paper focuses on the LCA of the AEL system, as it is a well-established technology (Sadeghi; Ghandehariun; Rosen, 2020; Zhang *et al.*, 2022). Four configurations were assessed, according to the electricity supply: i) Brazilian Grid, ii) Brazilian *marginal* Grid, iii) PV and iv) Wind power systems. The electrolyzer operation and manufacturing were based on Koj *et al.* (2017). The oxygen (O₂) co-produced with H₂ is vented into the atmosphere. This study employed a linear increase of 5% electricity demand for the AEL system over its lifetime to account for cell degradation (Roeder *et al.*, 2024). A stack lifetime of 80,000h or 10 years of operation was considered (Iyer *et al.*, 2024; Şahin, 2024).

To compare H₂ from wind and PV electricity, it was assumed that H₂ production would occur in both *on-grid* and *off-grid* configurations. *On-grid* refers to AEL systems (P7 and P9) connected to the Brazilian power Grid. In this configuration, the electrolyzer operates while connected to the transmission network, but the renewability of the electricity source is provided through a Power Purchase Agreement (PPA) with dedicated PV or wind power plants (Azevedo, 2022). PPAs guarantee that an amount of renewable electricity equal to the AEL daily consumption is injected into the grid, even if instantaneous PV or wind generation does not match real time electrolyzer operation.

To be classified as green H₂, the electrolysis plant must demonstrate that its electricity requirements are supplied by an additional (and newly built) renewable energy power plant (Caiafa; Kratena; Arto, 2025). Thus, in order to produce the energy needs for daily AEL *on-grid* operation, wind and PV power plants were oversized. In this way, although AEL consumes electricity from the Brazilian transmission network at any time, the oversized power plants ensure that the full amount of electricity for daily AEL operation is covered by renewable generation.

On the other hand, *off-grid* systems (P8 and P10) operate without any connection to the grid (Ceylan; Devrim, 2023). In this case, energy deficits (due to the RES intermittence) are compensated by batteries systems. In this configuration, the power capacity of both PV and wind power plants was also oversized to guarantee the electricity requirements for AEL and battery systems. A lithium-ion (Li-ion) battery with an energy density (ρ) of 275 Wh/kg (Vinardell *et al.*, 2023) is coupled with the AEL. The battery was sized (Equation 4) following the procedure described by Richard *et al.* (2020).

To meet the energy requirements for P8 and P10 pathways, a three-day period of autonomy (N)

was considered (Abubakar, 2020). For an *off-grid* system with relevant intermittence, a depth of discharge (*DoD*) of 50% (Akinyele; Belikov; Levron, 2017) and a battery charge output (η) of 90% (Vidueira; Contreras; Veziroglu, 2003) were adopted. The life cycle inventory (LCI) of battery manufacturing was taken from (Costa; Capaz; Bonatto, 2023). An average battery lifetime of 10 years was considered (Olabi *et al.*, 2021) and water requirements for its production were based on Mas-Fons *et al.* (2024).

$$\text{Battery size (ton)} = \left(\frac{P_{AEL} \times N + \epsilon}{DoD \times \eta \times \rho} \right) \times 1000 \quad (12)$$

Where, N is the days of autonomy of electrolysis systems; ρ is the battery density; *DoD* is the depth of discharge; η is the battery system efficiency; P_{AEL} is the AEL power and ϵ is the electricity required for H₂ compression.

The LCI for the PV power generation is detailed in Frischknecht *et al.* (2020), which includes module manufacturing and transportation from China to Brazil. Water requirements for the PV module manufacturing were taken from Meldrum *et al.*, (2013) and for the system operation were assumed to be negligible. See Tables A1 – A20 in the Appendix for more details. The PV power requirements (P_{PV}) to operate the AEL system throughout its lifetime were calculated as outlined in Müller *et al.*, (2021) using Eq. (14) and Eq. (15):

$$A = \frac{AEL_{\text{electricity demand}}}{\sum_{y=1}^T (1 - DR)^y \times I \times \eta \times PR} \quad (13)$$

$$P_{PV} = \frac{A}{PR \times I} \quad (14)$$

Where $AEL_{\text{electricity demand}}$ represents the electricity needed to power the electrolyzer systems, given in MWh/year; A is the total area of PV power system, in m²; DR is the annual degradation rate of 1% (Palmer *et al.*, 2021); I is the average Brazilian irradiation of 1,800 kWh/m²/year (Assunção; Schutze, 2017); P_{PV} corresponds to the power capacity of the PV system, given in MWp; PR is the performance ratio of 78% (Palmer *et al.*, 2021); T is the PV system's lifetime, set at 30 years and, η is the module efficiency of 17.5% (Frischknecht *et al.*, 2020).

For the wind power system, the LCI is based on Arvesen and Hertwich (2011). The inventory includes the manufacturing and the transportation of the turbine, rotor, and nacelle from a port in Denmark to Brazil (Fonseca; Carvalho, 2022; Gomaa *et al.*, 2019; Oebels; Pacca, 2013). Similar to the PV systems, WC during wind system operation was assumed negligible and WC for the wind turbine manufacturing was based on (Meldrum *et al.*, 2013). See Tables A64 – A67 in the Appendix for more

details. The power requirement (P_{Wind}) for the wind system was estimated as in Eq. (15):

$$P_{Wind} = \frac{AEL_{electricity\ demand}}{CF \times T} \quad (15)$$

where: $AEL_{electricity\ demand}$ is the electricity needed to power the electrolyzer systems, given in MWh/year; CF is the capacity factor of 41.5% based on the average wind electricity generated in Brazil in 2022 (ABEEólica, 2023) and T is the wind system lifetime which was set at 20 years (Arvesen; Hertwich, 2011).

For the AEL system powered by the Brazilian electricity Grid (P5 and P6), the average electricity mix for the past three years (2021-2023) was considered (Table S47 in the Supplementary Information): 61% hydro, 11% wind, 8% biomass, 5% photovoltaic and the remaining 15% corresponds to fossil resources (EPE, 2023a, 2024). The *upstream* inventory and the WC of Brazilian Grid were sourced from the Ecoinvent v3.9 database, using Brazilian providers (Ecoinvent, 2023).

Considering that an eventual AEL system based on the Brazilian Grid would represent an additional load on the power system, the environmental performance of H_2 production was also evaluated using the *marginal* emissions. The marginal operation of electricity corresponds to the energy source used, and its associated emissions, to supply an incremental increase in electricity demand. In the integrated Brazilian power Grid, hydropower, wind, photovoltaic, biomass and nuclear plants operate predominantly as low cost or must-run units. In this sense, as discussed by [Moreira et al. \(2014\)](#) and [Capaz et al. \(2021\)](#), the marginal electricity demand in Brazil is mainly supplied by natural gas thermal power plants.

Steam Reforming

The steam reforming (SR) process can employ natural gas, biomethane, or even ethanol to produce H_2 . However, SMR, based on natural gas, is still the conventional method for H_2 synthesis ([Agrawal et al., 2025](#)). In the SMR process, steam reacts with methane to create syngas, a mixture of H_2 and carbon monoxide (CO) ([Elaouzy; El Fadar, 2024](#)). This process uses natural gas both as a feedstock and as a heat source ([Patel et al., 2024](#)). The CO in syngas is then converted into CO_2 and additional H_2 through the water-gas shift (WGS) reaction, increasing the H_2 concentration ([Mio et al., 2023](#)). After the WGS reaction, the resulting H_2 gas undergoes pressure swing adsorption (PSA) to remove any remaining CO_2 and improve the H_2 purity ([Ji; Wang, 2021](#); [Nikolaidis; Poullikkas, 2017](#)).

SMR is a highly exothermic process, capable of generating an excess of steam beyond its consumption requirements ([Spath; Mann, 2001](#)). However, the current study did not consider any credits given for steam used in other applications, as done by ([Spath; Mann, 2001](#); [Wulf; Kaltschmitt, 2018](#)).

An alternative to natural gas is biomethane, which can be obtained from biogas released by

anaerobic digestion of municipal solid wastes (MSW) disposed in landfills (Borole; Greig, 2019). A potential solution for managing MSW is using it as a source of energy, offering an alternative to improper disposal methods while also reducing H₂ production costs and helping to add value to waste (Cho; Strezov; Evans, 2023; Lo Basso *et al.*, 2023).

However, the impurities of biogas require additional purification to meet the standards needed for the SR process (Cho; Strezov; Evans, 2023). Biogas purification is typically done through a PSA unit, which produces biomethane with 96% CH₄ by volume (Kohlheb *et al.*, 2021). During the PSA process, a small amount of methane may leak, estimated at 2.0% of the methane content in biomethane (96% CH₄) (Sun *et al.*, 2015).

In this study, biomethane, obtained from captured and purified (via PSA) landfill biogas, was assumed to replace – with an energy parity of 34.0 MJ/m³ (Argalis; Vegere, 2021) – natural gas in SR reactor without any modifications to end-user equipment (IEA, 2020).

The SR process of natural gas (SMR) and biomethane (SRBio) was modeled as outlined by Spath and Mann (2001) who describes an industrial plant capable of delivering 134.8 t H₂/day. SMR was evaluated under Brazilian conditions, with data on the natural gas market and electricity supply based on averages from ANP (2023) and Capaz *et al.*, (2021). Water requirements for the SMR and SRBio operation were taken from NELT (2022) and NREL (2018). The WC associated with natural gas processing and pipeline transportation was sourced from Meldrum *et al.* (2013).

In the case of SRBio, the WC associated with the PSA unit was sourced from Kohlheb *et al.* (2021). Following the recommendations of Antonini *et al.* (2020), no environmental burden was attributed to biogas itself. Therefore, only the environmental impacts from biogas purification are linked to biomethane. See Tables A4 – A5 in the Appendix for more details.

Another H₂ pathway gaining attention is the steam reforming of ethanol (SREtOH). The reaction between ethanol and steam generates a mixture of CO and H₂ - syngas - which then undergoes a WGS reaction to increase the H₂ yield, followed by a PSA process to improve the purity of the H₂ gas (Siddiqui; Dincer, 2019). The current study assessed the environmental performance of H₂ produced from steam reforming of sugarcane and maize ethanol.

The SREtOH operation was adapted from NREL (2018). Ethanol is employed both as feedstock and as fuel for the burner (Llorca *et al.*, 2013). Crop cultivation for both sugarcane and corn, as the current Brazilian feedstocks for ethanol production were included within the LCA study's boundaries.

The sugarcane cultivation data was sourced from (Bonomi *et al.*, 2016), which provides an average for Brazilian sugarcane production. The operation stage of the sugarcane EtOH mill were based on Junqueira *et al.* (2016). WC for sugarcane cultivation is negligible, as irrigation is not typically used in Brazil's main sugarcane production areas (Hernandes *et al.*, 2012; Hernandez; Bufon; Seabra, 2014), and WC for the sugarcane EtOH mill was taken from (Mekonnen *et al.*, 2018). See Tables A64 – A67 in the Appendix for more details.

The corn cultivation data was based on Moreira et al. (2020). Most corn ethanol is derived from second corn crop after soybean harvesting. This type of corn is known as “corn of opportunity”. In this sense, irrigation is not a common practice in soybean and second corn cultivation in Brazil.

Also, the blue WC for corn production is negligible, given that it represents only 1.3% of total WC for corn production (Mialyk *et al.*, 2022). WC at the industrial stage was derived from Mekonnen and Hoekstra (2011). Unlike the sugarcane EtOH mill, the energy demand in the corn ethanol plant is externally supplied by eucalyptus biomass (Eckert *et al.*, 2018). Eucalyptus cultivation was considered in this study based on the assumptions from Moreira et al. (2020).

The GHG emissions related to fertilizers and limestone as well as diesel burned in agricultural machinery were accounted for following the guidelines in ANP (2022) and Junqueira et al. (2016). The WC for fertilizer, agrochemical production and fossil diesel production was based on Mekonnen et al. (2018). Both corn and sugarcane ethanol are transported to the SREtOH facility where H₂ is produced. An average transport distance of 100 km was considered.

4.1.3. Environmental Impacts Categories

The assumptions related to the three environmental indicators evaluated in this study are presented as follows.

Fossil Energy Dependency

In LCA studies it is possible to estimate the total primary energy harvested from the environmental, consumed through a life cycle of a product (Leccisi; Rauegi; Fthenakis, 2016). Cumulative Energy Demand (CED) is particularly useful for assessing energy needs related to the extraction, manufacturing, operation, and disposal of resources within an energy system (Arvesen; Hertwich, 2015; Frischknecht *et al.*, 2015). CED quantitatively represents the total primary energy (both fossil and renewable) required from the ecosystem to produce a specific amount of usable energy carrier (Frischknecht *et al.*, 2015). It can also provide insights into the renewability and efficiency of an energy system (Huijbregts *et al.*, 2006).

In this study, Fossil Energy Ratio (FER) was selected as a metric to evaluate the life cycle energy performance of H₂ systems and assess the renewability of the energy system (Mayer *et al.*, 2020). FER expresses the ratio of the energy derived from the final fuel product (E_o) to the amount of primary fossil energy required for its production over the system's lifetime (E_i) (Sheehan *et al.*, 1998). The results from CED can be used to estimate FER in Eq. (16):

$$FER = \frac{E_o}{CED_{fossil}} \quad (16)$$

where E_o is the High Heat Value (HHV) of H_2 which is 142 MJ/kg H_2 (Ivy, 2004; Spath; Mann, 2001) and CED_{fossil} represents the primary fossil energy consumption estimated in HHV.

Global Warming Potential

The GWP of H_2 production pathways was estimated using the “IPCC 2021 GWP 100” method, which is based on the IPCC AR6 Climate Change 2021 report (Ecoinvent, 2023). The main GHGs: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrous oxide (N_2O) contribute to global warming by reflecting or absorbing a portion of solar radiation (Battista *et al.*, 2017). GHG emissions are a key factor in climate change, therefore, estimating them is essential when evaluating technologies for clean energy generation (Simons; Bauer, 2011).

Water Scarcity Footprint

Water scarcity is defined by the Food and Agriculture Organization (FAO) as the imbalance between water availability and demand, which can be measured either by the volume of water consumed or by factors like water quality and accessibility (FAO, 2012).

There are two approaches for assessing water use throughout the supply chain of products: the volumetric and the impact-oriented approaches (Mir; Nurdawati; Al-Ghamdi, 2025). The volumetric approach measures freshwater consumption and pollution. This methodology was designed by Hoekstra *et al.* (2012) who introduced an indicator to assess global water sustainability.

It quantifies the water embedded in goods and services traded globally, helping to assess three types of water footprints: blue, green, and grey. Green water refers to soil moisture from rainfall that evapotranspires from land used for crop cultivation, essentially stored as soil moisture. Blue water refers to the consumption of surface and groundwater, while grey water is linked to the pollution of water resources (Hoekstra *et al.*, 2009).

The Available Water Remaining (AWARE) is an impact-oriented indicator for assessing water consumption (WC) and water scarcity footprint (WSF) in LCA studies (Boulay *et al.*, 2018). The AWARE characterization factor (CF_{AWARE}) is a midpoint indicator that measures the remaining available water – or the water deprivation – per area in a specific watershed, once water demands for both human and aquatic ecosystems have been met (Shi; Liao; Li, 2020). It can be used to address the question: what is the potential for depriving another user when water is consumed in a particular region? (Boulay *et al.*, 2018; UNEP, 2016).

After evaluating a range of WSF indicators and criteria, (Andrade *et al.*, 2020) concluded that AWARE is the best method for assessing WSF in Brazil. Additionally, this method is widely accepted by LCA practitioners (Shi; Liao; Li, 2020) and is recommended by UNEP (2016) and aligns with ISO 14046:2014 (ISO, 2014).

The CF_{AWARE} is based on the normalized Availability Minus Demand (AMD) factor

($\text{m}^3/(\text{m}^2 \cdot \text{month or year})$) of a region in comparison with a global reference value ($0.0136 \text{ m}^3 \text{ world.} (\text{m}^2 \cdot \text{month})^{-1}$) (SimaPro, 2024; UNEP, 2016), while AMD factor represents the water needs for both human and aquatic ecosystems. An CF_{AWARE} factor of 1.0 corresponds to a region where the local AMD is equal to the global average, while a factor of 10 indicates a region where remaining water is 10 times less than the global average (Leão *et al.*, 2022).

In turn, the WSF, which was estimated for each H_2 production pathway, is exclusively based on blue WC weighted by CF_{AWARE} of each region (Eq. 17). It is worth pointing out that green and grey water consumption were not accounted for, as they are more appropriately assessed at land use or eutrophication aspects, respectively (Boulay *et al.*, 2018; Pfister *et al.*, 2017).

$$\text{WSF} = WC_{\text{Inter}} \times CF_{\text{AWARE_Global}} + WC_{\text{Brazil}} \times CF_{\text{AWARE_Brazil}} + WC_{\text{Brazil Operation}} \times CF_{\text{AWARE_Specific Basin}} \quad (17)$$

where WC_{Brazil} is the WC in Brazil; $WC_{\text{Brazil Operation}}$ is the WC for H_2 operation plant and WC_{inter} is the WC internationally.

WC_{Brazil} is the water consumed for energy feedstock production (such as sugarcane and maize ethanol, natural gas, electricity generation and biomethane) and therefore the country-level annual average AWARE ($CF_{\text{AWARE_Brazil}}$) was applied. Water consumed at H_2 factories, i.e. for cooling and steam generation systems and also as feedstock for electrolysis represents the $WC_{\text{Brazil Operation}}$ component. In this context, given the location-dependent nature of WSF assessments, regionalized $CF_{\text{AWARE_Specific Basin}}$ was applied for estimating WSF. The WC_{inter} component of WSF is attributed to WC for feedstock production that were assumed to be manufactured abroad (PV panels, wind turbines, battery manufacturing, and fertilizer production). In these cases, the $CF_{\text{AWARE_Global}}$ was used for estimating WSF. All CF_{AWARE} assumed here are reported in Appendix Table A68.

As stated above, $WC_{\text{Brazil Operation}}$ is influenced by the location where H_2 is produced. In this sense, specific regions were selected for each H_2 production configuration based on energy resource availability. AEL systems powered by wind and PV energy were assumed to operate in the Western Northeast Atlantic and São Francisco river basins, respectively, as these areas have the highest technical potential for wind and solar power (CEPEL, 2017; Pereira *et al.*, 2017).

AEL systems using electricity from the Brazilian grid were assumed to be located in the Paraná basin, due to its proximity to key maritime logistics hubs. The SREtOH pathways were also located in the Paraná basin. This reflects current production trends, as state of São Paulo, within the basin, is the country's main producer of sugarcane ethanol (Capitani *et al.*, 2024), while Mato Grosso is the leading corn producer (Gurgel *et al.*, 2024). Biomethane production was likewise assumed to be concentrated in the Paraná basin, particularly in São Paulo state (EPE, 2023b), and the Southeast region is Brazil's largest consumer of natural gas (EPE, 2020).

To reveal comparative performance trends across production pathways, the three indicators (FER, GWP and WSF) were normalized and represented in a ternary plot, allowing simultaneous visualization of their relative contributions. For the construction of the ternary diagram, each indicator was normalized by computing its inverse value relative to the arithmetic mean of the three metrics for each pathway. This procedure enabled expressing the indicators as proportional shares that sum to unity, which is needed for ternary coordinate transformation and facilitates the interpretation of trade-offs among the evaluated routes.

4.2. Life Cycle Assessment of Hydrogen use for Ammonia production

The selected green NH_3 pathways are described in Figure 11 which comprises the main stages of NH_3 synthesis: wind and PV electricity generation, PEM for H_2 production, air separation unit which used for N_2 production and the H-B system.

For evaluating the carbon intensity of green and fossil NH_3 a function unit of 1 kg of produced NH_3 was selected. The method chosen was Recipe midpoint (Huijbregts *et al.*, 2016). The Simapro software (SimaPro, 2024) and Ecoinvent version 3.9 database were used for the estimation of GWP of NH_3 (Ecoinvent, 2023). Aligned to the objectives of socioeconomic analysis, only GWP category was evaluated for ammonia production. A cradle-to-gate analysis was conducted. Impacts associated with the construction and the manufacturing of H_2 plant (PEM, and SMR) and for H-B synthesis were considered. Decommissioning and end life cycle analysis are out of scope of this study.

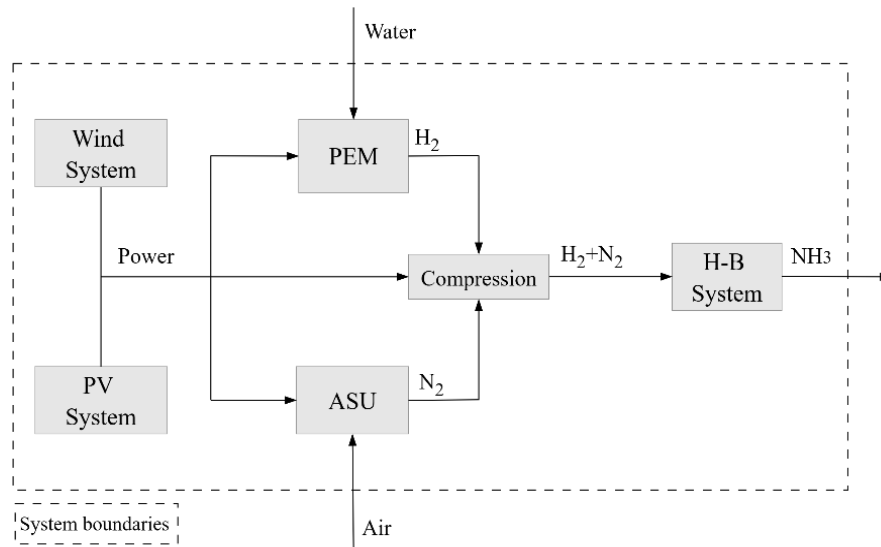


Figure 11 – H-B system loop

Source: Own elaboration

Life cycle inventory for H-B construction is derived from (Vinardell *et al.*, 2023) and for its operation is based on (Arrigoni *et al.*, 2024). For PEM manufacturing and operation, inventory was

based on (Gerhardt-Mörsdorf *et al.*, 2024). Inventory for the PV power system was based on (Frischknecht, 2020; Wang *et al.*, 2022). For the wind power plant, the inventory was obtained from (Arvesen; Hertwich, 2011; Fonseca; Carvalho, 2022; Oebels; Pacca, 2013). In the case of fossil NH₃ derived from natural gas, H₂ is derived from SMR which was based on the assumptions reported by (Spath; Mann, 2001).

Preliminary results indicated that the H₂ production pathways with the lowest GWP were those based on renewable electricity generated from wind and PV resources (see section 5.1). For this reason, these H₂ production routes were selected to assess the levelized costs and potential social impacts associated with the use of H₂ for NH₃ synthesis.

4.3. I-O Analysis

This section presents the main assumptions considered for modeling the I-O system used to assess the socioeconomic impacts resulting from green NH₃ production in the Brazilian economy.

4.3.1. I-O model Analysis

The I-O analysis is an economic framework based on empirical data from a specific region, designed to capture the interindustry flows among different sectors of the economy (Miernyk, 2020; Simas; Pacca, 2014). It is a useful method to assess the inter-dependence between different industries as well as it can apply for measurement of direct and indirect impacts associated with a new sector (Gupta *et al.*, 2023) such as green NH₃.

The social and environmental impacts of production and consumption can be assessed by analyzing each sector's factors of production. These factors are the requirements and impacts linked to the economic output of an industry (Simas; Pacca, 2014).

The basic model of an I-O table consists in a matrix composed of rows that represent the output that an industry or sector sells to the other industries or sectors listed and columns that show the inputs purchased by an industry or sector from those listed along the left (Miernyk, 2020).

The output from industry i is used as input industry j (intermediate demand) and to final demand (households and government consumption, capital expenditure and exports) (Caiafa; Romijn; De Coninck, 2024; Guilhoto, 2011). The Total Output of a sector is the sum of intermediate and final demands and it must be same of the Total Input (which is the sum of intermediate demand, taxes minus subsidies on products, value-added and imports) of the sector (Gupta *et al.*, 2023).

The Total Output vector can be represented as X , the intermediate demand is given by the matrix Z , and the final demand is represented by the vector F . The effects of shocks or impacts can be calculated:

$$X = Z + F \quad (18)$$

Rewriting the intermediate demand as a proportion of the Total Output, the equation above becomes:

$$X = AX + F \quad (19)$$

Where A is the matrix of technical coefficients, defined by $a_{ij} = \frac{z_{ij}}{x_j}$ which is the direct interdependence between the sectors of an economy. The term a_{ij} indicates the inputs needed from sector j by sector i . Assuming that the coefficients of the I-O matrix remain constant and the matrix $(I - A)$ is nonsingular and I is the identity matrix, the solution to the Eq. (19) is:

$$X = LF \quad (20)$$

Where:

$$L = (I - A)^{-1} \quad (21)$$

Where L is known as the Leontief inverse matrix. Each element of the Leontief inverse represents the Total Output required from sector i to produce one unit of final demand from sector j . The Total Output includes both direct and indirect requirements. To estimate changes in demand (output) for a given change in final demand:

$$\Delta X = L \cdot \Delta F \quad (22)$$

The basic Leontief model considers only the effects on final demand as an exogenous effect (Guilhoto, 2011; Miller; Blair, 2009), meaning that the final demand vector (F) is seen as an independent variable and is determined outside the model.

I-O can also be employed for impact analysis which measures how a change in the final demand vector (F) reflects in the macroeconomic indicators. For impact analysis, a technical coefficient, denoted as γ_i is defined for a given impact indicator (employment creation, GDP analysis, GHG emissions, energy consumption):

$$\gamma_i = \frac{q_i}{x_i} \quad (23)$$

Where q_i is the total value indicator for industry i , and x_i is the Total Output for industry i . In turn, the diagonal matrix of technical coefficients ($\hat{\Gamma}$) is then multiplied by the inverse of the Leontief matrix L to create the total requirements matrix (Γ) for a given impact indicator:

$$\Gamma = \dot{\Gamma} \cdot L \quad (24)$$

Where $\dot{\Gamma}$ is the determinant:

$$\dot{\Gamma} = \begin{bmatrix} \gamma_i & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \gamma_n \end{bmatrix} \quad (25)$$

Γ is then multiply by the change in demand ΔF final to estimate the change in the quantity of the impact indicator (ΔQ) under analysis (Prasad, 2024):

$$\Delta Q = \Gamma \cdot \Delta F \quad (26)$$

The impacts of a new industry on the I-O matrix were based on (Miller; Blair, 2009, p. 633) who describes two approaches for introducing a new sector into the economy: i) through the use of a new final demand vector only or, ii) by adding a new element to the technical coefficients table for the economy.

The first approach was used in this study (Figure 12). In the *construction* phase, the shocks were implemented considering the existing sectors in current Brazilian I-O, this means that the new sectors – H₂ production from wind or PV, and NH₃ production via H-B synthesis – were not introduced in the I-O table. As stated earlier, the part of CAPEX imports and domestic production and manufacturing of utilities was considered in this analysis.

In the *operation* stage, the macroeconomic impacts were also evaluated for an electrolytic NH₃ system in which the electricity demand is fully supplied through a Power Purchase Agreement (PPA). In this case, there are no CAPEX and OPEX associated with the construction of RES (as done in the case of PV and wind electricity generation), as electricity is not self-generated. The PPA costs were obtained from (CCEE, 2025), whose average monthly price for the Brazilian market over the past five years is 146.51 BRL/MWh (in 2018 constant values).

In this sense, three new final demand vectors were developed to represent the *operation* costs of green NH₃, differentiated according to the electricity source employed, without adding new rows or columns to the I-O table (Figure 12). At the *operation* phase to avoid creating an artificial demand for a product that already exists (despite of fossil origin and with a different productive structure), it was assumed that domestic fossil NH₃ production within the *Manufacture of organic and inorganic chemicals* sector would be displaced by the same mass of green NH₃, which replaces domestic fossil production.

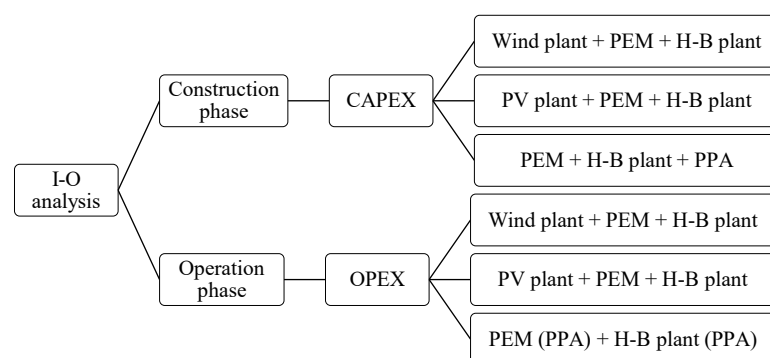


Figure 12 – I-O adjusted structure for domestic green NH₃ production

Source: Own elaboration

It was assumed that the cost of NH₃ produced from PV, wind and PPA should be equal to the cost of fossil-based NH₃ produced in Brazil. The cost of fossil NH₃ was taken as the import cost of this commodity in 2020. In that year, imports of anhydrous NH₃ amounted to USD 83,616,203.00, equivalent to 284 Mt (Brasil, 2025), representing an average cost of USD 294/t NH₃. The entire imported volume corresponded to fossil-based NH₃, since renewable NH₃ accounts for a negligible share of global production and its costs are several times higher than those of conventional NH₃.

As state earlier, green NH₃ has a high production cost than fossil conventional NH₃. In this sense, to make green NH₃ cost-equivalent to fossil NH₃, the cost difference (subsidy) was distributed according to the distribution of government expenditures in final demand, assuming that the government would cover these costs. Two scenarios were developed to estimate the required subsidies, differing in the subsidy level needed to make green NH₃ from PV and wind electricity competitive with fossil-based NH₃.

Table 4 – Scenarios Assumptions related to subsidies for domestic ammonia production

Scenario	Assumptions	Calculation Basis	Expected Outcome
I – Direct Cost Difference	Green NH ₃ must be made cost-competitive with fossil NH ₃	Subsidy estimated as the direct gap between the production cost of PV, wind and PPA- based NH ₃ and fossil NH ₃	Provides the minimum subsidy level to equal production costs
II – Carbon Abatement Cost Adjustment	Environmental benefits are monetized and used as a reference for subsidy allocation	Subsidy estimated as the difference in carbon abatement cost from replacing fossil NH ₃ with PV- and wind-based NH ₃ , adjusted by the cost gap between green and fossil NH ₃	Aligns subsidy allocation with climate benefits, supporting the internalization of environmental externalities

For assessing the macroeconomic impact of green NH₃ industry in Brazil, a new final demand vector for the *construction* and *operation* stages was structured based on a plant with production capacity of 400 t NH₃/day. This volume corresponded to the domestic fossil production of NH₃ in 2020 (146,911 t NH₃/year) which is assumed to be replaced by new green NH₃ production (Brasil, 2021).

The most recent 2018 I–O table (includes 68 sectors) provided by (Guilhoto; Sesso Filho, 2010) was used, which, although not recent, according to (Miller; Blair, 2009), the productive structure of an economy changes little over a horizon of 5 years. All the cost associated with CAPEX and OPEX were categorized based on Brazilian National Classification of Economic Activities (CNAE) (IBGE, 2025a).

Generally, CAPEX and OPEX are given in terms of producer prices¹⁰, however, I–O analysis often assesses the impacts in terms of basic prices. In this sense, CAPEX and OPEX were transformed into basic prices considering the ratio between the basic prices and the producer prices for each sector of I–O tables derived from Brazilian System of National Accounts (IBGE, 2025c).

4.3.2. Green Ammonia Industry Structure

The inputs for green NH₃ industry were collected from different sources and were assigned into the already existing sectors in the Brazilian I–O table. It was considered two phases: *construction* and *operation*.

4.3.3. Construction Phase

The inputs for the impact analysis of the *construction* phase are commonly expressed in cost per installed capacity of the plant. In the investment phase, the CAPEX (Table 5), which belongs to new final demand (F), was evaluated; therefore, only the investments in equipment and materials necessary for the construction of the NH₃ plant were considered, meaning that the new sector for producing green NH₃ has not been introduced.

Table 5 – Producer prices of components for NH₃ *construction* stage

System	Components	CAPEX (2018 M USD)	Supply sectors	Reference
PEM	Stack	27.88	Imported	(European Hydrogen Observatory, 2024)
	Balance of Plant	9.48	Manufacturing of electrical equipment	(European Hydrogen Observatory, 2024)
	Contingency	14.55	Financial intermediation, insurance and pension funds	(Caiafa; Romijn; De Coninck, 2024)
H–B	Compressor and heat exchanger	13.06	Manufacture of machinery and mechanical equipment	(Morgan, 2013)
	NH ₃ reactor	2.56	Manufacture of machinery and mechanical equipment	(Morgan, 2013)

¹⁰ Producer price corresponding to the difference between purchaser's prices and the sum of gross trade and transport margins + product taxes less subsidies on consumers (SIAP, 2008).

System	Components	CAPEX (2018 M USD)	Supply sectors	Reference
PV	Storage tank	3.39	Manufacture of fabricated metal products, except machinery and equipment	(Morgan, 2013)
	Air separation unit	0.12	Manufacture of machinery and mechanical equipment	(Rivarolo <i>et al.</i> , 2019)
	Equipment and auxiliary systems	221.8	Imported	(EPE, 2022)
	Civil works	37.51	Construction	(EPE, 2022)
	Connection and transmission	31.98	Manufacturing of electrical equipment	(EPE, 2022)
	Others cost	18.80	Other administrative and support service activities	(EPE, 2022)
	Land	2.15	Real estate activities	(Fearnehough; Skribbe, 2022)
	Contingency	62.27	Financial intermediation, insurance and supplementary pensions	(Fearnehough; Skribbe, 2022)
	Equipment and auxiliary systems	132.54	Manufacture of machinery and mechanical equipment	(EPE, 2022)
	Civil works	23.88	Construction	(EPE, 2022)
Wind	Connection and transmission	16.31	Manufacturing of electrical equipment	(EPE, 2022)
	Contingency	15.28	Financial intermediation, insurance and supplementary pensions	(Fearnehough; Skribbe, 2022)
	Transport	17.42	Land transport	(Fearnehough; Skribbe, 2022)
	Others cost	31.96	Financial intermediation, insurance and supplementary pensions	(Fearnehough; Skribbe, 2022)

Many of the technological inputs and materials required for the construction of the plant are imported. In this sense, to more accurately reproduce the national industry or domestic economy, the impacts of the investment phase were estimated considering the share of the inputs are imported; that is, they were not introduced into the I–O model. The share of imported and domestic investment for each part of the construction phase is described below

PV and Wind Power Systems

Operational parameters considered for modeling both PV and wind power systems are presented in Table 6. PV power system has a capacity factor of 18% (Assunção; Schutze, 2017; Pupin, 2019) and

the wind power plant has a capacity factor of 41% (ABEEólica, 2023).

Table 6 – Power plants operational parameters

Parameter	Unit	PV	Wind
Electricity production	GWh/year	1,368	1,368
Capacity factor	%	18%	41%
Power installation	MW	868	381
System lifetime	years	25	25

Source: Own elaboration

The CAPEX for PV and Wind power generation were taken from (EPE, 2022; Fearnough; Skribbe, 2022). In the case of the PV industry, this study considered that there is no national production of panels and inverters. According to¹¹ (Araújo; Saavedra; Boeira, 2023a; Greener, 2024) the entire production chain of solar PV panels, modules, and inverters occurs abroad.

On the other hand, the wind energy sector is well-established in Brazil, thanks to tax incentives, public investments, and coordinated policies that have promoted the nationalization of the wind generation supply chain components (Gouvêa; Silva, 2018). It is assumed that 100% of the wind supply chain is domestic, according to estimates (Araújo; Saavedra; Boeira, 2023b). Furthermore, the activities related to the installation, operation and maintenance of both PV and wind power plants are provided entirely by local companies and workers.

To be considered “green” H₂, the electricity used for supplying PEM must be produced from an additional source of RES (Caiafa; Kratena; Arto, 2025). In this sense, both PV and wind systems were oversized to generate the electricity requirements (yearly) of PEM and H-B systems, by considering the capacity factor above-mentioned (see Table 6).

PEM system

The assumptions for PEM operation were derived from Gerhardt–Mörsdorf *et al.* (2024) and they are displayed in Table 7.

¹¹ Only 3.8% of installed PV panels are manufacturing in Brazil.

Table 7 – PEM operational parameters

Parameter	Unit	Value
Electricity demand	GWh/year	1.3
Compression	kWh/kg H ₂	0.7
Annual hours operation	h/year	8,000.0
System lifetime	years	20.0
Pressure delivery	bar	30.0
Power installation	MW	177.4
Water deionized demand	ton H ₂ O/year	241
Production rate H ₂	kg H ₂ /h	3,420

Source: Own elaboration

Electrolyzer PEM type was selected due to its advantages over available electrolytic technologies: compact design, high current densities, high voltage efficiency, fast response to power input, short start-up time, lower operating temperature (50 – 80 °C), high H₂ purity (>99.99%), and high operating pressure (around 80 bar), which reduces energy costs associated with compression and storage systems (Smith; Hill; Torrente–Murciano, 2020; Vinardell *et al.*, 2023). Also, PEM coupled with H–B synthesis has a level of maturity between 6 – 7 (Smith; Hill; Torrente–Murciano, 2020). CAPEX for PEM system was based on the assumption that there was a scaling effect of PEM electrolyzers. In this sense, it was assumed that the cost for PEM stack is given by a scale factor of:

$$\text{Stack cost} = (P)^{-0.364} \quad (27)$$

where P is the power capacity of PEM (Cantane *et al.*, 2025b).

A stack replacement of electrolyzer necessary after 10 years or 80,000 h of PEM operation (Iyer *et al.*, 2024; Şahin, 2024). Up to 2023, 60% of production, in terms of PEM power capacity, is concentrated in China (IEA, 2024a). In this sense, it was assumed that all PEM systems components are imported.

Haber–Bosh System

The operation parameters for H–B systems showed in Table 8 were based on (Arrigoni *et al.*, 2024).

Table 8 – H–B operational parameters

Parameter	Unit	Value
H–B electricity demand	MWh/year	55,091
H–B power capacity	MW	20.2
H ₂ demand	t/year	25,925
NH ₃ output (yearly)	t/year	146,911
NH ₃ output (daily)	t/day	402.5
N ₂ demand	t/year	120,986
ASU electricity	MWh/year	16,685
Compressor capacity	MW	10.6
Cooling water consumption	kt/year	26,443
Catalyst demand	kg/year	1,616
Annual hours operation	h	8,300

Source: Own elaboration based on Arrigoni et al. (2024)

According to Djire *et al.* (2025), CAPEX for H–B systems comprises the capital expenditures for compression, ASU, NH₃ reactor and heat exchanger systems. The assumptions took in the current study was based on the plant described by Morgan (2013) which was designed to produce 300 t NH₃/day. In order to scaling up the cost and technical parameters assumed by Morgan (2013) it was used a scaling factor for each equipment based on Gerloff, (2021) and Morgan (2013):

$$\frac{C_1}{C_2} = \left(\frac{x_1}{x_2}\right)^n \quad (28)$$

- C₁ – cost of component
- C₂ – known cost of component
- X₁ – capacity of component
- X₂ – known capacity of component
- n – scaling factor¹²

Heat exchanger and NH₃ reactor costs were estimated on the assumptions presented by (Morgan, 2013). Compressor and ASU costs were assessed according to Rivarolo *et al.* (2019). It was considered the replacement of catalytic iron bed in H–B process after 10 years of operation Guerra *et al.* (2020).

The manufacturing of all H–B components occur in Brazil. As in H₂ production systems, NH₃ costs also decrease with increasing production capacity, ranging from 2,400 USD/t to 900 USD/t for onshore wind-based NH₃ production systems with installed capacities of 20 MW and 300 MW,

¹² Compressor = 0.7; Heat exchanger = 0.59 and Ammonia reactor = 0.67

respectively (Cantane *et al.*, 2025a).

4.3.4. Operation Phase

For the *operation* phase it was considered that domestic fossil NH₃ would be all replaced by green NH₃. In 2020, domestic industry produced 146,911 t NH₃, i.e., 400 t NH₃/day of fossil NH₃ derived from natural gas (Brasil, 2021). The cost for the *operation* phase for each system is described as following in Table 9:

Table 9 – Inputs from different industries for the NH₃ *operation* phase

System	Components	OPEX (M USD 2018/year)	Supply sectors	Reference
PEM	Water	0.0002	Water, sewage, and waste management	(Santana <i>et al.</i> , 2023)
	O&M	2.21	Repair and installation of machinery and equipment	(NREL, 2018)
	Financial and Insurance services	0.86	Financial intermediation, insurance, and supplementary pensions	(Lazard, 2021)
	Stack replacement	17.06	Repair and installation of machinery and equipment	
	Employment factor	0.08 FTE/MW	–	(NREL, 2018)
	Salaries ¹³	24,758 USD/FTE	Electricity, natural gas, and other utilities	(IBGE, 2025b)
	PPA ¹⁴	22.9	Electricity, natural gas, and other utilities	
H-B	O&M	0.48	Repair and installation of machinery and equipment	
	Fe-catalyst	0.03	Manufacture of organic and inorganic chemicals, resins, and elastomers	
	Cooling water	2.01	Water, sewage, and waste management	
	Employment factor	0.08 FTE/MW	–	(NREL, 2018)
	Salaries	26,476 USD/FTE	Architectural, engineering, testing and technical analysis, and R&D services	(IBGE, 2025b)
	Electricity	0.15	Electricity, natural gas, and other utilities	
	Operation	9.12	Electricity, natural gas, and other utilities	
PV	O&M	12.16	Repair and installation of machinery and equipment	
	Salaries	22,038 USD/FTE	Electricity, natural gas, and other utilities	(IBGE, 2025b)
	Employment factor	1.1 FTE/MW	–	(Caiafa; Romijn; De Coninck, 2024).
	Operation	5.01	Electricity, natural gas, and other utilities	

¹³ Salaries are reported in per-unit values.

¹⁴ Only in the case where self-generation of wind and PV electricity is not considered.

System	Components	OPEX (M USD 2018/year)	Supply sectors	Reference
	O&M	6.72	Repair and installation of machinery and equipment	
	Salaries	22,038 USD/FTE	Electricity, natural gas, and other utilities	(IBGE, 2025b)
	Employment factor	0.64 FTE/MW	–	(Caiafa; Romijn; De Coninck, 2024)

Source: Own elaboration

Three new final demand vectors will be constructed based on the assumptions outlined in Section 4.3.1 to estimate the impacts resulting from green NH₃ production, considering the substitution of domestically produced fossil NH₃.

PV and Wind Power Systems

The OPEX for PV and wind electricity generation includes maintenance for panel cleaning, vegetation management, site security, preventive maintenance, land lease, remote monitoring, insurance and property taxes. The maintenance of PV panels occur in every 6 months and in 2 years for wind (Campbell, 2016; Forsyth *et al.*, 2017). Operation costs for both PV and wind power system were derived from Fearnehough and Skribbe (2022). Employment factor was assumed to be 0.64 full time equivalent (FTE) per MW and 1.1 FTE/MW for wind and PV operation systems, respectively (Caiafa; Romijn; De Coninck, 2024). The average salaries of the Brazilian *Electricity and Gas* sector was assumed for PV and wind systems operation.

PEM system

The components of OPEX for PEM operation it was derived from Lazard (2021) and NREL (2018). The PEM lifetime system is set at 20 years. For maintenance and repair, a value of 3% of CAPEX is assumed, which includes stack replacement after 10 years (NREL, 2018). It was set an employment factor of 0.08 FTE/MW for PEM system (NREL, 2018). The Brazilian *Industrial Gas Manufacturing* sector average salary was considered for PEM operation (IBGE, 2025b).

Water is the main input for the electrolysis system. Stoichiometrically, 9.0 liters of water is necessary for producing 1.0 kg of H₂. However, studies have reported that water consumption can range of 20 – 24 liters per kg of H₂ (IRENA; Bluerisk, 2023). In this sense, it was assumed that an average volume of 8,9 kg H₂O/kg H₂ (Carmo *et al.*, 2013). Water cost for PEM system was assumed to be 4.9 BRL/m³ (Santana *et al.*, 2023).

Haber–Bosh System

The OPEX for H–B systems includes operation and maintenance cost that was set at 1.5% of CAPEX (Guerra *et al.*, 2020). NH₃ synthesis requires iron catalyst (Bora *et al.*, 2024). It was assumed a catalyst demand of 0.011 g Fe/kg NH₃ (Vinardell *et al.*, 2023). Water requirements for cooling process was considered based on Vinardell *et al.* (2023). Salaries were obtained from the average wage of the *Intermediate Manufacturing sector for Fertilizers* (IBGE, 2025b). A FTE of 0.08 FTE/MW was assumed to be the same as PEM. It was considered a H–B system lifetime of 25 years (Djire *et al.*, 2025).

4.3.5. Levelized Cost of Hydrogen and Ammonia

The levelized cost of H₂ (LCOH) and NH₃ (LCOA) were estimated based on Paulino De Azevedo *et al.* (2025). LCOA was used as the reference for calculating the macroeconomics impacts that may arise from a green NH₃ industry in Brazil. The nominal discount rate (r) and inflation rate (f) were assumed to be 8% and 5%, respectively (Paulino De Azevedo *et al.*, 2025).

For NH₃ systems coupled with RES self-generation units (wind and PV), the power plants (PP) were sized to meet the nominal power demand of both the electrolyzer and the H–B systems. In these cases, in addition to the investment costs of the electricity generation plants, there are also tariffs¹⁵ associated with the use of the electricity distribution system, which were obtained from (ENEL, 2025).

$$LCOH = \frac{\sum_{i=1}^n (CAPEX_{PP+PEM} + OPEX_{PP,i+PEM,i}) \left(\frac{1+f}{1+r} \right)^i}{\sum_{i=1}^n \frac{M_{H_2,i}}{(1+r)^i}} \left[\frac{USD}{kg H_2} \right] \quad (29)$$

Where n is the project lifetime; i is the year, $CAPEX_{PP+PEM}$ and $OPEX_{PP,i+PEM,i}$ are the capital expenditure and operation expenses for the power plant (PP) and for electrolysis (PEM), respectively, $M_{H_2,i}$ is the output H₂ kilogram per year.

$$LCOA = \frac{\sum_{i=1}^n (CAPEX_{PP+PEM+HB} + OPEX_{PP,i+PEM,i+HB,i}) \left(\frac{1+f}{1+r} \right)^i}{\sum_{i=1}^n \frac{M_{NH_3,i}}{(1+r)^i}} \left[\frac{USD}{t NH_3} \right] \quad (30)$$

Where n is the project lifetime; i is the year, $CAPEX_{PP+PEM+HB}$ and $OPEX_{PP,i+PEM,i+HB,i}$ are the capital expenditure and operation expenses for PP , PEM and H-B,

¹⁵ 14.53 BRL/MWh for medium voltage

respectively and $M_{NH_3,i}$ is the output NH_3 in kilogram yearly.

For NH_3 production systems fully supplied with renewable electricity under a PPA, the portion corresponding to the investment and operation costs of the power generation plant (PP) was excluded from the calculation of the LCOH and LCOA, in order to avoid double counting, since PPA contracts already include CAPEX and OPEX expenses in their total cost structure.

5 RESULTS AND DISCUSSION

This chapter presents the results of the environmental and economic indicators evaluated in this study. It begins with the presentation and discussion of the LCA results for H₂ and electrolytic NH₃ production systems, followed by the discussion of the input–output model results associated with green NH₃ production in Brazil.

5.1. Hydrogen Life Cycle Assessment

The main results for FER, GWP, and WSF are summarized in Table 10. The CED and WC used for FER and WSF estimation, respectively, are also explicitly presented.

Table 10 – Main results for FER, GWP, WSF

Pathways	FER	CED (MJ _{fossil} /kg H ₂)	GWP (kg CO _{2e} /kg H ₂)	WSF (m ³ _{eq} H ₂ O/kg H ₂)	WC (m ³ H ₂ O/kg H ₂)
SMR	0.5	308.6	11.5	0.4	0.03
SREtOH Corn	8.8	16.1	2.9	3.0	0.10
SREtOH Sugarcane	6.3	22.5	2.9	6.4	0.23
SRBio	40.5	3.5	3.6	1.2	0.05
AEL BR Grid	1.9	72.8	7.9	38.9	1.50
AEL BR Grid (marginal)	0.1	991.4	39.1	7.0	0.28
AEL PV (<i>on grid</i>)	7.1	20.1	2.0	1.3	0.03
AEL PV (<i>offgrid</i>)	1.3	113.4	11.4	60.9	1.42
AEL Wind (<i>ongrid</i>)	24.5	5.8	0.6	0.7	0.02
AEL Wind (<i>offgrid</i>)	2.1	67.3	6.7	59.1	1.38

Source: Own elaboration

In general, GWP and FER are expected to exhibit similar trends, as fossil energy consumption is directly associated with GHG emissions. This relationship, however, is not observed for the P4 pathway, which showed the highest FER, but a disproportionately lower GHG reduction potential compared to other pathways. P4 can also deliver approximately 40-fold more energy (as H₂) per unit of fossil energy consumed throughout its life cycle. Nonetheless, this pathway can achieve 70% reduction in GWP relative to P1. GHG emissions of P4 are mainly attributable to fugitive methane emissions (61.8 g CH₄/kg H₂) at the biogas upgrading process.

Conversely, P1 and P6, both supplied by natural gas, presented the lowest FER values – due

to the intensive use of fossil fuels – and the highest GWPs, driven by fossil fuel (natural gas) combustion as an energy source. However, the difference in FER (0.1 to 0.5) is not proportional to the difference observed in GWP values (11.5 to 39.1). P1 pathway uses natural gas both as a feedstock and as an energy source (127 MJ CH₄/kg H₂), whereas in P6, natural gas is intensively used for electricity generation, with a conversion efficiency of 54% (Ecoinvent, 2023), to supply the electrolysis process (894 MJ CH₄/kg H₂).

When examining water-related indicators, WC and WSF exhibited broadly similar trends, highlighting another important dimension of environmental performance. Among AEL pathways, P6, P8 and P10 scenarios revealed the highest WSF values (38-60 m³_{eq} H₂O/kg H₂). These results are primarily explained by the WC associated with the production of metals used in battery manufacturing (4.0 m³ H₂O/kg battery or 1.3 m³ H₂O/kg H₂) and by evaporative losses from hydropower reservoirs, which accounts for 61% of Brazil's electricity generation (EPE, 2024). The relatively high WSF of P8 and P10 systems is further influenced by the characterization factor adopted for battery manufacturing associated with *intermediate* stage (CF_{AWARE_Global}), which is approximately 20 – fold greater than the average value assumed for Brazil (CF_{AWARE_Brazil}).

For P7, WC is mostly attributed to the *upstream* stage (PV module manufacturing) whereas in P9, WC is concentrated on the *operation* stage (water consumed at electrolysis plant). For these pathways, total life cycle WC was estimated at 33.2 and 15.8 L/kg, respectively. These values are quite close to that estimated for the P1 (24.0 L/kg H₂), while H₂ obtained from corn or sugarcane ethanol resulted in approximately double the WC.

A critical challenge when siting green H₂ facilities in Brazil is the geographical mismatch between renewable energy potential and water availability. Regions with abundant solar and wind resources often experience significant water scarcity. Consequently, locating electrolysis plants in these areas can lead to a higher WSF values compared to conventional H₂ production (P1). This issue is particularly pronounced for P9 route. The *operation* stage of this pathway is proportionally highly water intensive – despite showing one of the lowest water consumption levels among the evaluated pathways. Furthermore, the water scarcity characterization factor (CF_{AWARE_Specific Basin}) is elevated in the region where the P9 pathway is located.

Although it is not feasible to carry out a direct comparison between the findings of this study and those in existing literature without standardizing the data to facilitate a fair assessment, it was possible to identify overarching trends and evaluate the overall performance on a global scale. Table 3 presents the main findings of this research and compares them with those reported in the literature; notably, none of the studies evaluated all three aspects simultaneously.

Table 11 - LCA results of the reviewed papers

Reference	WC (m ³ /kg H ₂)	WSF (m ³ _{eq} /kg H ₂)	GWP (kg CO _{2eq} /kg H ₂)	CED (MJ _{fossil})	FER (MJ H ₂ /MJ _{fossil})	Boundaries	Pathway
(Hajjaji <i>et al.</i> , 2016b)	-	-	5.59	4.5	33	Cradle-to-grave	Biogas Reforming
(Abawalo; Pikoń; Landrat, 2025)	0.05	-	5.5	1.95	73	Cradle-to-grave	Biogas Reforming
(Yoo; Kim; Song, 2018)	-	-	7.4 (without carbon credits) -0.77 (with carbon credits)	-	-	Well-to-wheel	Biogas Reforming
(Hren <i>et al.</i> , 2023)	-	-	4.0	-	-	Cradle-to-distribution	Biogas Reforming
(Arfan <i>et al.</i> , 2023)	-	-	2.13	-	-	Cradle-to-gate	Biogas Reforming
(Olaitan; Bertagni; Porporato, 2024)	7.4	-	-	-	-	Cradle-to-gate	Biomass Reforming
This study	0.05	1.2	3.6	3.5	40.5	Cradle-to-gate	Biomass Reforming
(Mann; Spath, 2004)	-	-	0.97	-	13.2	Cradle-to-gate	Wind Electrolysis
(Zhang <i>et al.</i> , 2023)	-	-	-	9.1	15.6	Cradle-to-gate	Wind Electrolysis
(Patel <i>et al.</i> , 2024)	-	-	0.6	-	-	Cradle-to-gate	Wind Electrolysis
(Du <i>et al.</i> , 2024)	0.04	-	-	-	-	Cradle-to-gate	Wind Electrolysis
(Shi; Liao; Li, 2020)	0.02	0.4	-	-	-	Cradle-to-gate	Wind Electrolysis
(Bionaz <i>et al.</i> , 2022)	-	-	4.9	-	-	Cradle-to-use	Electrolysis (PV + Wind + diesel generator)
This study	0.02	0.7	0.6	5.8	24.5	Cradle-to-gate	Wind Electrolysis
(Palmer <i>et al.</i> , 2021)	2.5	-	-	-	4.6	Cradle-to-gate	PV Electrolysis
(Mio <i>et al.</i> , 2024)	-	-	-	-	7.22	Cradle-to-grave	PV Electrolysis
(Sadeghi; Ghandehariun; Rosen, 2020)	-	-	3.1	-	-	Cradle-to-grave	PV Electrolysis
(Patel <i>et al.</i> , 2024)	-	-	2.5	-	-	Cradle-to-gate	PV Electrolysis
(Du <i>et al.</i> , 2024)	0.07	-	-	-	-	Cradle-to-gate	PV Electrolysis
(Shi; Liao; Li, 2020)	0.04	1.0	-	-	-	Cradle-to-gate	PV Electrolysis
(Gandiglio <i>et al.</i> , 2022)	-	-	6.6	-	-	Cradle-to-use	Electrolysis (PV + diesel generator)
This study	0.03	1.3	2.0	20.1	7.1	Cradle-to-gate	PV Electrolysis
(Dufour <i>et al.</i> , 2012)	-	-	28.1	28	0.4	Cradle-to-gate	Electrolysis (grid 14% renewable)
(Mio <i>et al.</i> , 2023)	-	-	23.5	-	-	Cradle-to-gate	Electrolysis (56% fossil grid)
(Siddiqui; Dincer,	-	-	28.6	-	-	Well-to-	Electrolysis

Reference	WC (m ³ /kg H ₂)	WSF (m ³ _{eq} /kg H ₂)	GWP (kg CO _{2eq} /kg H ₂)	CED (MJ _{fossil})	FER (MJ H ₂ /MJ _{fossil})	Boundaries	Pathway
(2019)						pump	(fossil U.S. grid)
(Hren <i>et al.</i> , 2023)	-	-	23.0	-	-	Cradle-to-distribution	Electrolysis (EU fossil grid)
(Shi; Liao; Li, 2020)	0.1	3.0	-	-	-	Cradle-to-gate	Electrolysis (Australia fossil grid)
This study	0.28	7.0	39.6	991.4	0.1	Cradle-to-gate	Electrolysis (100% grid fossil)
(Mio <i>et al.</i> , 2023)	-	-	4.32	-	-	Cradle-to-gate	Electrolysis (100% renewable grid)
This study	1.5	38.9	7.9	72.8	1.9	Cradle-to-gate	Electrolysis (85% renewable grid)
(Spath; Mann, 2001)	-	-	11.88	-	0.66	Cradle-to-gate	SMR
(Olaitan; Bertagni; Porporato, 2024)	0.05	-	-	-	-	Cradle-to-gate	SMR
(De Souza <i>et al.</i> , 2021)	0.3	-	-	-	-	No information	SMR
(Mehmeti <i>et al.</i> , 2018)	5.77	247.0	12.3	-	-	Cradle-to-grave	SMR
This study	0.03	0.4	11.5	308.6	0.5	Cradle-to-gate	SMR
(Siddiqui; Dincer, 2019)	-	-	12.2	-	-	Well-to-pump	Corn US Ethanol Reforming
(Mehmeti <i>et al.</i> , 2018)	2.24	94.0	9.2	-	-	Cradle-to-grave	Corn Ethanol Reforming
This study	0.23	6.4	2.9	22.5	6.3	Cradle-to-gate	Brazilian Corn Ethanol Reforming
(Khila <i>et al.</i> , 2016)	-	-	7.26	-	-	Cradle-to-gate	Beet Tunisia Ethanol Reforming
(Hajjaji <i>et al.</i> , 2013)	-	-	9.2	-	-	Cradle-to-gate	Wheat Swedish Ethanol Reforming
(De Souza <i>et al.</i> , 2021)	9.7	-	-	-	-	No information	Brazilian Sugarcane Ethanol Reforming
This study	0.1	3.0	2.9	16.1	8.8	Cradle-to-gate	Brazilian Sugarcane Ethanol Reforming

5.1.1. Fossil Energy Dependency

As mentioned above, P4 delivers the highest FER (40.5) which demonstrates the lowest dependency on fossil fuels across pathways assessed. This result is comparable to the value reported by Hajjaji et al. (2016), who found a fossil CED of 4.5 MJ/kg H₂, corresponding to a FER of 33.3. The

difference between the FER calculated in this study and that reported by Hajjaji et al. (2016) can be attributed to electricity requirements for biogas reforming: while their study assumes electricity derived from fossil fuels, this work considered electricity demand for both biogas upgrading and reforming stage are supplied by the Brazilian power Grid – 85% renewable.

Also, Abawalo et al. (2025) assessed the CED for H₂ produced via biogas reforming. Waste feedstock (considered to have no environmental burden) was employed for biogas production. Systems boundaries included the credits given for the displacement of synthetic fertilizers by using the digestate from AD as a fertilizer. The process has a high FER of 73 (CED of 1.95 MJ/kg H₂) which is influenced, mostly by the electricity consumed at the AD and reforming stages, with most energy sourced from the fossil-fueled grid.

For P2 and P3, the energy return estimated for *intermediate* stages (ethanol production) is high for both corn (6.2) and sugarcane (7.0), in Brazilian conditions, leading to a favorable FER for H₂ produced via SREtOH. In the same way, Marques et al. (2024) found that sugarcane ethanol in Brazil can deliver an average FER of 7.4, and in the case of corn ethanol produced in Brazil, FER is estimated in 11.3 (Alonso Pippo; Alves, 2022).

P7 and P9 also exhibit high FER (7.1 – 24.5), owing to Brazil's favorable load factors related to wind and PV systems. This means that more electricity can be produced over the lifetime of PV and wind power plants. A FER of 13.2 was assessed by Mann and Spath (2004) for AEL powered by wind, which indicates a significantly higher energy return of this system. In the same way, a FER of 15.6 (CED of 9.1 MJ/kg H₂) was estimated by Zhang et al. (2023), for wind electrolysis.

Energy performance of P5 – even with a 85% of RES (EPE, 2024) – and P8 and P10 pathways is low (1.3 up to 2.1). Even though in a small percentage, the share of primary fossil energy for electricity production (15%) in the Brazilian power Grid became relevant in an energy intensive process such as electrolysis (90% of CED is associated with electricity generation, see Figure 2). For example, Dufour et al. (2012) estimated a FER of 0.4 (CED of 28 MJ/kg H₂) for H₂ produced via AEL powered by an energy grid with only 14% renewable share, a value closely related to the FER of 0.1 reported in the present study. The lowest FER was found in P6, reflecting the complete dependence on fossil fuels (natural gas) for electricity generation and the limited efficiency in converting natural gas into electricity.

In the case of P8 and P10, the *intermediate* stage associated with battery manufacturing is a considerable contributor to the overall environmental load of these energy systems. Palmer et al. (2021) evaluated an energy return of 4.6 for an AEL system based on PV power with 25% efficiency, coupled with battery storage. They highlighted that PV module and battery production significantly influence the fossil energy inputs of the system, which aligns with the findings of this study that *upstream* and *intermediate* processes dominate fossil energy consumption in P7 and P8 configuration (Figure 2). Furthermore, a study by Mio et al. (2023) estimated an energy return of 7.2 for H₂ produced from AEL powered by PV electricity, a value closely to the FER reported in this study.

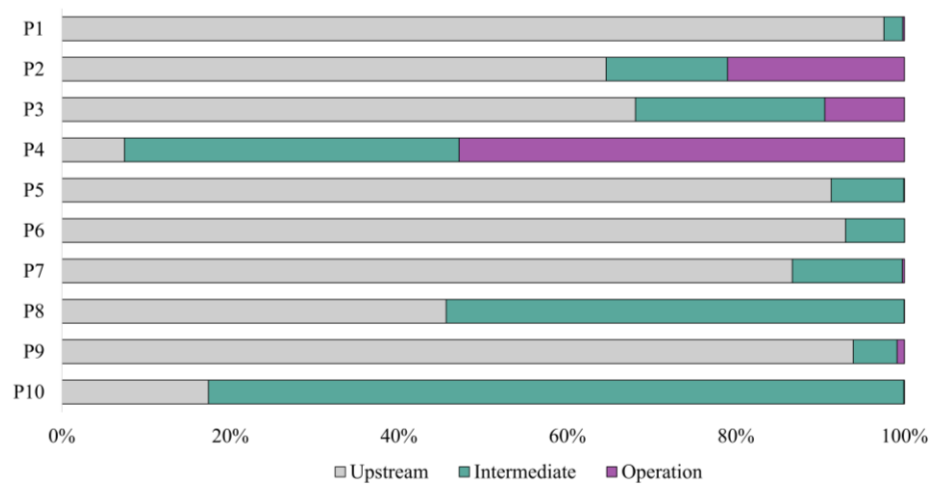


Figure 13 – Contribution analysis for Cumulative Energy Demand (CED)

For P1, FER is aligned with value reported by Spath and Mann (2001) who found a FER of 0.66 for SMR, i.e. for each 1.0 MJ of fossil energy consumed in the whole supply-chain only 0.66 of energy is delivery in form of H₂. The low renewability of P1 is attributed to natural gas consumed through the H₂ lifecycle. As done by Spath and Mann (2001) the energy contained in the natural gas used to feed the reforming stage was included for FER estimation.

5.1.2. Global Warming Potential

As shown, the largest GWP reduction (94%) relative to the baseline P1 pathway is achieved by P9. Figure 3 illustrates that the GWP is determined by the energy source supplying the electrolyzer, since AEL operation itself does not produce direct GHG emissions. This trend is supported by studies like Sadeghi et al. (2020), who found that 88% of the 3.08 kg CO₂eq/kg H₂ it is concentrated in upstream processes, i.e. PV module manufacturing. Similarly, Patel et al. (2024) reported GWP values of 0.6 and 2.5 kg CO₂eq/kg H₂ for PV and wind powered PEM, respectively, with at least 90% of the GWP associated with upstream stages.

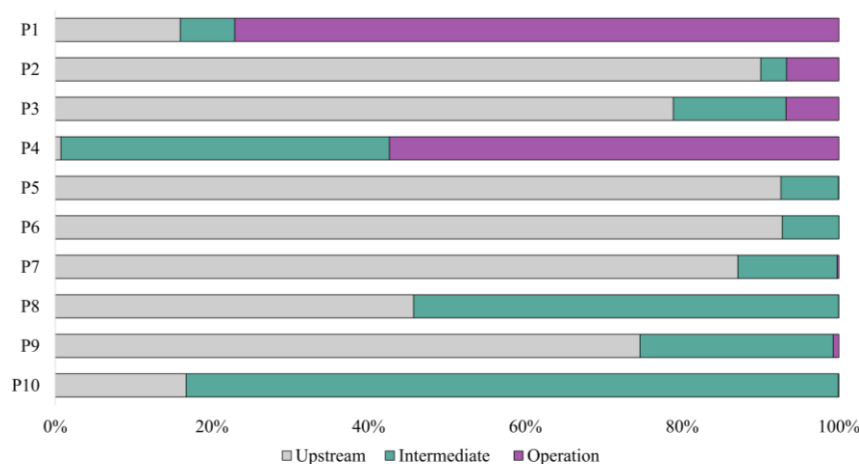


Figure 14 – Contribution analysis for Global Warming Potential (GWP)

It's also worth noting that PV panels and batteries are primarily manufactured in countries where electricity generation still relies on fossil fuels, which increases their *upstream* GHG emissions. In the case of *off-grid* systems, GWP is strongly influenced by battery production, which increases GWP by factors of 5 and 11-fold for P8 and P10, respectively compared to *on-grid* systems (P7 and P9)

The GWP of P4 varies significantly depending on biogas origin and system boundaries (Bakkaloglu; Hawkes, 2024). Present study found a GWP of 3.6 kg CO_{2eq}/kg H₂. By considering emission credits (8.2 kg CO_{2eq}/kg H₂) for avoiding biogas flaring, Yoo et al. (2018) reported a negative GWP of -0.77 kg CO_{2eq}/kg H₂ for landfill biogas and without upstream credits, a GWP of 7.4 kg CO_{2eq}/kg H₂. As no emissions credits have been accounted for in the present study, the high renewability of the Brazilian power Grid and lower CH₄ fugitive emissions from biogas upgrading resulted in a GWP value lower to than reported by Yoo et al. (2018)

Also, Hren et al. (2023) reported a GWP of 4.0 kg CO_{2eq}/kg H₂, including *upstream* emissions from biogas produced from corn silage. In contrast, Arfan et al. (2023) reported a GWP of 2.13 kg CO_{2eq}/kg H₂ from biogas obtained in AD process. Their study considered that natural gas is used to meet the energy needs of the steam reforming unit while the P4 process assed in the current work is supplied by biomethane. Also, 73% of emissions come from the digestion itself (Arfan *et al.*, 2023) which corroborates the findings of the this research

In another study, Abawalo et al. (2025) estimated a GWP of 5.47 kg CO_{2eq}/kg H₂ for biomethane reforming. According to them, the *upstream* processes are responsible for 85% of total GWP mainly due to electricity consumption, construction of the AD plant, and fugitive methane emissions from AD process (0.28 kg CH₄/kg H₂). Also, the *intermediate* GHG emissions accounted for 58% of the GWP by the present study (Figure 3), which is associated with methane leakage at PSA unit (62 g CH₄/kg H₂) and the remaining contribution is linked to methane emissions at steam reforming plant (0.06 kg CH₄/kg H₂), which were not considered by Abawalo et al. (2025).

For P2 and P3, GWP is highly influenced by the crop cultivation stage, which contributes more

than 80% of the total emissions (Figure 3). Brazilian H₂ derived from corn ethanol results in a 76% lower GWP than U.S. H₂ corn ethanol (12.2 kg CO_{2eq}/kg H₂), primarily because Brazilian corn distilleries use biomass to supply their energy demand, whereas U.S. facilities rely on fossil fuels (Siddiqui; Dincer, 2019). In contrast, Khila et al. (2016) estimated a GWP of 7.26 kg CO_{2eq}/kg H₂ for H₂ derived from beet ethanol. Their finding showed that electricity consumption and agriculture crop cultivation contributed to 52% and 38% of GWP, respectively. In another study, wheat-based H₂ showed a GWP of 9.2 kg CO_{2eq}/kg H₂, with 54% of emissions stemming from biomass cultivation and 45% from natural gas combustion in the ethanol mill (Hajjaji *et al.*, 2013).

Due to the high share of renewable energy in the Brazilian power Grid, the current study found that P5 has a 72% lower GWP compared to the values reported by Siddiqui and Dincer (2019), who conducted a well-to-pump analysis of H₂ production and found a GWP of 28.6 kg CO_{2eq}/kg H₂ for electrolysis based on the U.S. grid (34.2% coal and 31.6% natural gas). Moreover, Hren et al. (2023) calculated a GWP of 23 kg CO_{2eq}/kg H₂ for an electrolyzer supplied by 2019 EU electricity grid (43% fossil). For *marginal* operation (P6), GWP reached a quite close value that is cited by papers above. This high GWP is attributed to the emission factor associated with electricity generation from natural gas (0.63 kg CO_{2eq}/kWh).

For P7 and P9, *upstream* processes - such as the manufacturing of PV modules and wind turbines – contribute over 80% and 60%, respectively, of the GHG emissions (Figure 3). This trend is supported by Sadeghi et al. (2020) and by Patel et al. (2024), who reported in a cradle-to-gate analysis, that about 90% of the GWP in PV- and wind-based PEM systems originates from *upstream* processes.

Furthermore, Bionaz et al. (2022) and Gandiglio et al. (2022) evaluated the environmental impacts of electricity generation for a remote community. In both studies, electricity is supplied by a fuel cell powered by electrolytic H₂ derived from RES, supplemented by a diesel generator and lithium battery storage systems. A GWP of 6.6 kg CO_{2eq}/kg H₂ was estimated, with approximately 70% of GWP attributed to electricity generation by the diesel generator, 32% to PV manufacturing panels, and about 10% to the production of batteries (Gandiglio *et al.*, 2022). Meanwhile, Bionaz et al. (2022) reported a GWP of 4.9 kg CO_{2eq}/kg H₂, with 32% attributed to diesel electricity generation, 22% to PV panel manufacturing, and around 7% to battery manufacturing (Bionaz *et al.*, 2022).

5.1.3. Water Scarcity Footprint

Although water consumption for H₂ production is not typically the focus of discussions, it has become increasingly important, especially in regions already facing water scarcity. With more than 35% of green and blue H₂ installed capacity located in water stressed areas (IRENA; Bluerisk, 2023), it's essential to evaluate the WC associated with H₂ production and understand the potential strain on water resources caused by the implementation of H₂ systems.

From Table 2, a relationship can be observed between high WC and the WSF indices. For P7,P8,

and for P10, the WC_{inter} component represents a critical factor. In these cases, the combination of the CF_{AWARE_Global} index and the high-water use in *upstream* and *intermediate* (water consumed for PV panel and battery manufacturing) processes results in greater water resource deprivation than in the fossil conventional P1 route.

From another perspective, direct $WC_{Brazil\ Operation}$ at the H_2 production plants plays a relevant role for P1, P4, and P9 pathways (Figure 4). In such cases, the WSF is strongly influenced by the geographic location of H_2 production. For instance, pathway P9 is located in a region where the water scarcity index is approximately four times the Brazilian average. Likewise, the high electricity consumption in the P4 pathway, compared with P1, results in a higher WSF for P4.

In the case of P2, the WC in *operation* stage represents more than 50% of total WC, mainly associated with $WC_{Brazil\ Operation}$ at steam reforming plant. On the other hand, the WSF of P3 refers to the volume of water consumed (WC_{Brazil}) in distilleries (*intermediate* stage) which is ten times larger compared to ethanol corn production.

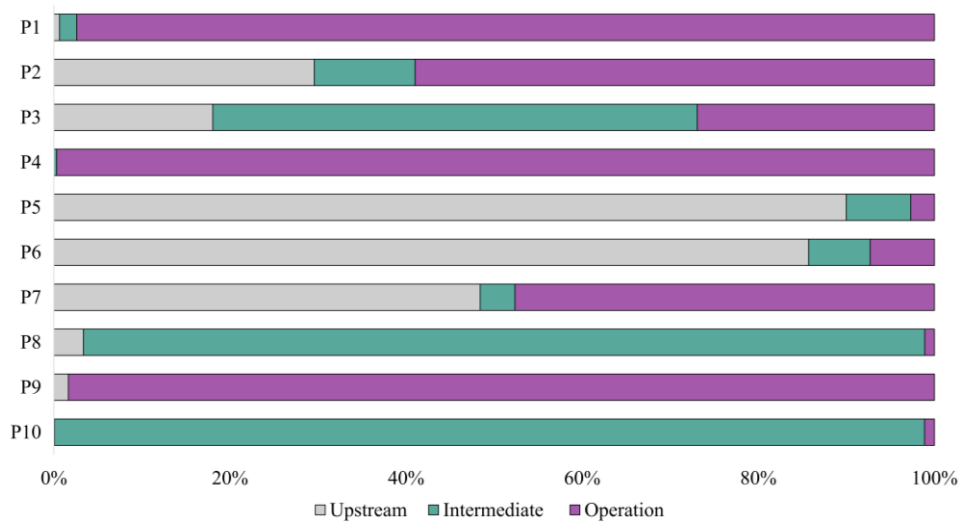


Figure 15 – Contribution analysis for Water Consumption (WC)

In turn, WC for P7 and P9 is closely related to average values calculated by Du et al. (2024) who found 0.04 and 0.07 $m^3\ H_2O/kg\ H_2$ for wind and PV electrolysis, respectively. Similarly, Shi et al. (2020) estimated WC values of 0.1, 0.04 and 0.02 $m^3\ H_2O/kg\ H_2$ and a WSF based on AWARE method of 3.0, 1.0, and 0.4 $m^3_{eq}\ H_2O_{eq}/kg\ H_2$ for electrolysis powered by the Australian power Grid, PV, and wind systems, respectively. Both studies demonstrate that *upstream* WC associated with PV panels manufacturing is the main contribution to total WC for H_2 derived from PV electricity. In the case of P9, water is mainly consumed at *operation* stage. In addition, WC (1.5 $m^3\ H_2O/kg\ H_2$) and WSF (38.9 $m^3_{eq}\ H_2O/kg\ H_2$) for P5 route are higher than those reported by Shi et al. (2020) due to water consumed in hydroelectricity generation, as mentioned above. WC for P1 was estimated to be 0.03 $m^3\ H_2O/kg\ H_2$

which is aligned with Olaitan et al. (2024).

Different WC and WSF results for the SMR and SREtOH Corn pathways were reported by Mehmeti et al. (2018), who applied a cradle-to-grave approach to assess these indicators. The authors reported WC values of $5.77 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ for SMR and $2.24 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ for the SREtOH Corn pathway, as well as AWARE values of 247 and $94 \text{ m}^3_{\text{eq}} \text{ H}_2\text{O/kg H}_2$, respectively. A direct comparison with the authors' findings cannot be performed because their study lacks explicit information on the inclusion of blue or green water, which may substantially modify the outcomes (De Souza *et al.*, 2021). Nevertheless, Mehmeti et al. (2018) highlighted that biomass-based H_2 pathways may face challenges associated with supply chains that are strongly linked to water use, particularly in agricultural stages, as in the case of the corn ethanol pathway.

De Souza et al. (2021) estimated a WC of $0.3 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ and $9.7 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ for SMR and SREtOH, respectively. The WC reported by those authors is higher than found by the currently study: 0.03 and $0.23 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ for P1 and P3, respectively. These authors included green water related to sugarcane crop, which explains the discrepancies in comparison with this study. This may affect the results since the content of green water is essential for the development of these crops (Hernandes; Bufon; Seabra, 2014; Mialyk *et al.*, 2022; Mir; Nurdiawati; Al-Ghamdi, 2025).

Olaitan et al. (2024) reported a WC of $7.4 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$ for biomass gasification (wood chips) with most of the WC arising from wood chip production and the biodiesel used in the scrubber unit. By contrast, the current work reported the WC for P4 was lower ($0.05 \text{ m}^3 \text{ H}_2\text{O/kg H}_2$), because biogas is considered a waste product, and the main WC is linked to the PSA unit. Additionally, this pathway resulted in a low WSF, which can be attributed to both the low value $CF_{\text{AWARE_Specific Basin}}$ of the region and the relatively small WC.

5.1.4. Environmental Tradeoffs

Figure 5 presents the environmental performance of the ten H_2 production pathways (at log scale) according to their FER, WSF and GWP, the latter reflected by circle size. The results reveal clear *trade-offs* among the three indicators. Pathways P5, P8 and P10 exhibit modest FER values but also the highest WSF and relatively large GWP. In contrast, pathways P4 and P9 show the most favorable overall profiles, combining high FER with low WSF and small GWP points, thus representing the environmentally preferred options. Intermediate pathways (P2, P3 and P7) present moderate WSF and FER values with mid-range GWP impacts, while P1 showed a low water usage but retains a moderate climate impact and a higher fossil dependence (low FER). Pathway P6 performs the worst among all options, characterized by lowest FER, high WSF and the largest GWP. Overall, the distribution of pathways underscores that improvements in renewability do not uniformly translate into lower water or climate impacts, highlighting the necessity of integrated assessment across energy, water and carbon dimensions.

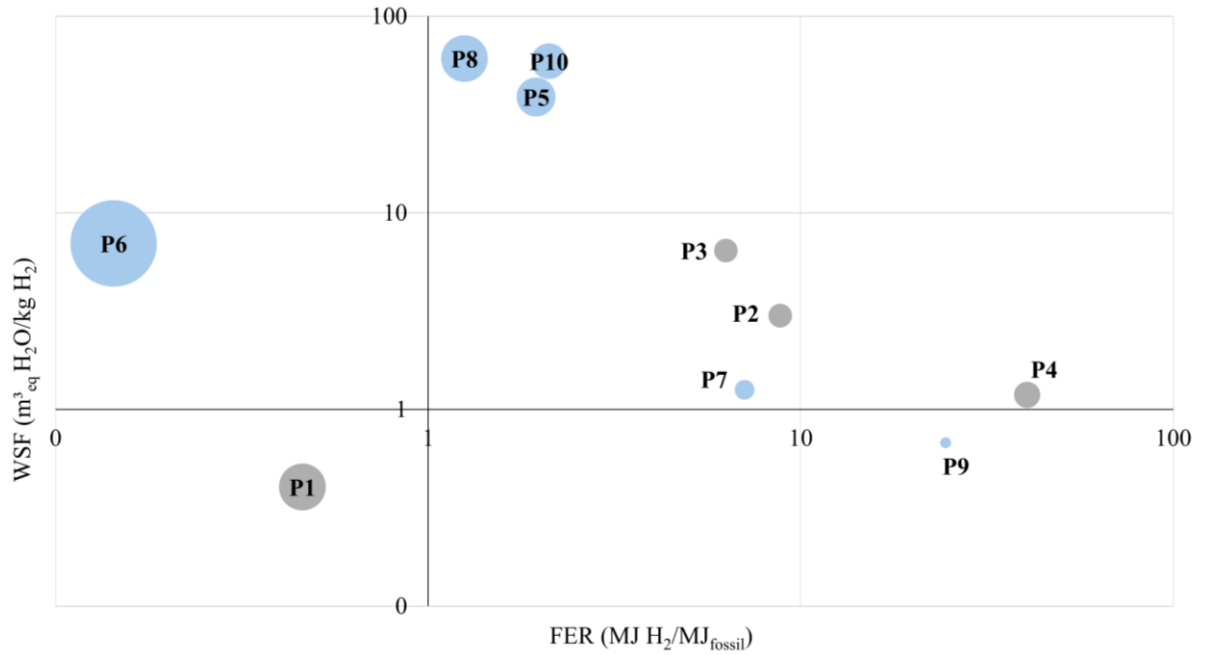


Figure 16 – *Trade-offs* in H₂ production pathways

Blue points indicate water alkaline electrolysis. Grey points are routes based on steam reforming.

P4 and P9 showed the best environmental performance among all pathways. Their high FER values, low pressure on water resources, and reduced contribution to GWP are directly related to the assumptions adopted in this study. In the case of P4, biogas was assumed to carry no environmental burden because it is derived from waste, while its biogenic carbon content and the low water requirements of the industrial processing stages further enhance its performance. For P9, AEL powered by wind electricity benefits from the average capacity factor of wind generation in Brazil (that ranges between 45-55% while the global average capacity factor is 35% according to (Cacciuttolo; Navarrete; Cano, 2025)), which ensures high energy returns and due to the low WC throughout the life cycle of H₂ produced via this electrolytic route.

H₂ production pathways based on AEL may exhibit higher GWP and WSF than the SMR pathway, along with a low FER, as observed in the case of the P6 which showed the most unfavorable global environmental indicators – characterized by the highest GHG emissions and a diminished H₂ renewability.

Due to methane leakage at the biogas purification process, GWP associated with P4 route was moderate despite its high FER. In this sense, minimizing fugitive methane emissions is necessary to guarantee the sustainability of the biomethane, since these emissions can exceed those from the natural gas supply chain per unit of energy delivered (Bakkaloglu; Hawkes, 2024).

In the case of P9, this pathway achieved the lowest GWP and a high FER; however, its WSF

was higher than P1, mainly due to the high-water scarcity index in the regions where P9 implemented. Pathways such as P8, P2 and P3 presented lower GWP than P1 but exhibited higher WSF, largely due to the water intensive nature of PV panel and battery manufacturing, as well as water consumed for fertilizer production and for sugarcane and corn mill water needs. These findings highlight the importance of reducing WC throughout the H₂ supply chain, even for renewable pathways.

When RES is employed for H₂ production, it can reduce GWP and WC and increase energy performance. The abundance of RES (solar, wind, and hydro), Brazilian expertise with ethanol production, and the availability of urban and agro-industrial waste provide promising perspectives for developing a diversified and low-carbon H₂ economy. However, several challenges remain – the integration of RES with battery can have a negative influence on GWP and WSF indicators, as shown for *off-grid* (P8 and P10) compared to those configurations without energy storage systems (P7 and P9).

Additionally, AEL remains energy intensive, even when powered by clean energy sources. The energy source used to produce fuels and electricity are decisive factors for water scarcity impacts, thus being necessary assess the WC and GHG emissions throughout the entire supply chain of H₂ production from a LCA perspective (Mehmeti *et al.*, 2018). In contrast, fossil pathways, despite their greater energy efficiency and lower costs, remain associated with elevated carbon intensities (Elaouzy; El Fadar, 2024). In the case of P2 and P3, agricultural-based pathways may also compete for water resources with other sectors, even though Brazilian sugarcane and corn cultivation are not directly water intensive.

The contribution analysis (Figure 2 and Figure 3) revealed that *upstream* and *intermediate* processes in PV and wind systems represent a critical aspect for CED and GWP indicators. The environmental impacts assessed are largely driven by stages occurring outside Brazilian borders, where H₂ is produced. Consequently, in many cases, improving these indicators lies beyond the control of the local H₂ producer. Nevertheless, the LCA demonstrated that accounting for the production aspects is essential for a comprehensive and accurate assessment of the environmental performance of H₂ production pathways.

In this context, public policies should prioritize the domestic manufacturing of key equipment and inputs required for H₂ synthesis. Nationalizing these components could significantly improve the environmental indicators assessed. Furthermore, the use of MSW presents an opportunity to reduce emissions and add value to currently underutilized waste streams.

5.2. Green Ammonia Life Cycle Assessment

The GWP for NH₃ was estimated in 0.20, 0.48 and 2.17 kg CO₂eq/kg NH₃ for NH₃ based on wind, PV and natural gas (baseline), respectively (Table 12). In all cases, mostly GHG emissions arising from H₂ production. The high electricity requirements for H₂ production are the reason this stage contributed, in the majority, for the total GWP of electrolytic NH₃. In the case of PV- and wind-based NH₃, all the emissions are indirect emissions, i.e. embodied emissions in PV panels and wind turbines

manufacturing. The consumption of natural gas consumption for H₂ synthesis contributes largely for GWP of fossil NH₃. Also, compared to the conventional NH₃, a reduction of 90% can be achieved when RES is applied.

Table 12 – GWP of ammonia production pathways

Pathways	Hydrogen production	Haber–Bosch	Total (kg CO ₂ eq/kg NH ₃)
NH ₃ (Wind)	0.08	0.12	0.20
NH ₃ (PV)	0.34	0.14	0.48
NH ₃ fossil	2.06	0.11	2.17

Source: Own elaboration

Our results are aligned with those reported by Vinardell *et al.* (2023) who estimated a GWP of 0.9 and 0.3 kg CO₂eq/kg NH₃ for PV–based and wind–based NH₃, respectively. In their study, a battery system was incorporated to ensure continuous electricity supply for both PEM and H–B units, but its contribution to the GWP was negligible and only marginally affected costs (6% for wind–based and 7% for PV–based NH₃). For conventional NH₃, based on natural gas, our results are close to 2.0 kg CO₂eq/kg NH₃ reported by Mersch *et al.* (2024) and Vinardell *et al.* (2023).

In a cradle–to–gate analysis, Boero *et al.* (2021) evaluated emissions of 2.8, 0.7 and 0.3 kg CO₂eq/kg NH₃ for fossil (natural gas), PV– and wind–based alkaline electrolysis routes, respectively. The authors emphasizing that H₂ production is the dominant driver of GHG emissions, which corroborates our findings. NH₃ derived from a renewable–based electricity mix (52% wind, 22% PV, 18% biomass, and 8% hydro) in Germany resulting in emissions of 0.15 kg CO₂eq/kg NH₃, representing a 97% reduction compared to natural gas–based NH₃ (2.8 kg CO₂eq/kg NH₃) (Chisalita; Petrescu; Cormos, 2020). The GWP for green (50% PV and 50% wind) NH₃ was also evaluated by (Brito, 2025) using I–O approach who found a GWP of 0.34 kg CO₂eq/kg NH₃ which is close to the average assessed by our LCA analysis.

5.3. I–O Analysis

This section presents and discusses the results of the I–O analysis after applying the shocks and estimating the behavior of the evaluated socioeconomic indicators. Additionally, this section includes the estimation of the LCOH and the LCOA, which were used to assess the macroeconomic indicator through I–O analysis.

5.3.1. Levelized Costs

CAPEX cost is the main contributor to the total LCOA for both NH₃ wind and PV. CAPEX represents 89% of total cost for both NH₃ wind and PV (Figure 17). The difference between the LCOH

of PV – H₂ and wind – H₂ arises mainly from the higher CAPEX and OPEX associated with PV power plants compared to wind.

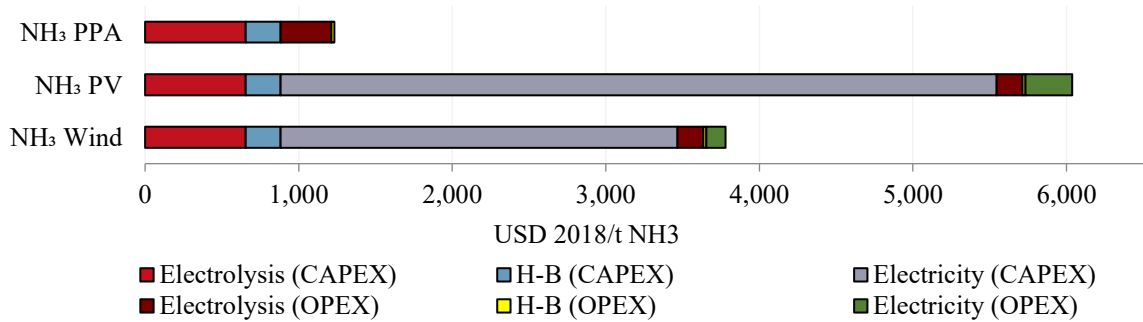


Figure 17 – CAPEX and OPEX composition

Source: Own elaboration

All the pathways return a LCOH higher than prices set by Petrobras in Brazil, which range between 2 – 3 USD/kg H₂ for H₂ derived from natural gas (Alcantara *et al.*, 2025). As can be seen, Table 13 shows the LCOH of H₂ and LCOA of NH₃.

Table 13 – Levelized cost

Electricity Source	Wind	PV	PPA
LCOH (USD 2018/kg H ₂)	4.28	6.94	3.30
LCOA (USD/t NH ₃)	1,196	1,908	778.2

Source: Own elaboration

Cuevas–Castillo *et al.* (2025) evaluated PEM–based electrolytic NH₃ supplied by offshore wind, reporting an LCOA of 891 USD/t NH₃ – reducible to 482 USD/t NH₃ if electricity costs drop by 50%. H₂ production dominates both OPEX (92%) and CAPEX (57%). In the same way, Djire *et al.* (2025) found that electrolyzers dominate both CAPEX (90%) and OPEX (97%) in green NH₃ plants, with the H–B system, compression, and ASU contributing only minor shares.

The LCOH assessed by current study is align with value reported by (Cantane *et al.*, 2025a) who estimated, for a PEM of 100 MW, a LCOH of 5.2 USD/kg H₂ powered with onshore wind and 6.8 USD/kg H₂ using PV and, in both cases, considering a PPA cost of 12.2 USD/MWh.

Also, Barros Souza Riedel *et al.* (2024) explores the synergy between PV and hydroelectricity sources for H₂ produced in a pilot plant located in the Itumbiara Hydroelectric Plant, Brazil. For a share composition of 40.6% PV and 59.4% of hydro, a LCOH of 13.0 USD/kg H₂ was found. The high LCOH is attributed to the small capacity electrolysis, the usage of primary data and due to the assumption that no subsidies were given for H₂.

By increasing H₂ production through AEL powered by wind electricity, the LCOH can be reduced to values between 1.20 and 0.64 USD/kg H₂ (Alcantara *et al.*, 2025). However, according to their findings, achieving economic viability at a zero-net H₂ price requires the plant to generate additional revenues from by-product sales, particularly hospital oxygen at 5.00 USD/m³ and surplus wind electricity at 75.38 USD/MWh. On the other hand, although O₂ pricing may enhance the economic feasibility of H₂, the market for electrolytic O₂ is unlikely to be promising given the large volumes produced as a by-product and the limited demand to absorb such supply (Maggio; Squadrito; Nicita, 2022).

Additionally, a LCOH of 1.26 – 1.64 USD/kg was estimated for electrolysis powered by the Brazilian grid, reaching cost parity with fossil H₂ only when revenues from hospital O₂ sales (58% of total revenues) were included; without this by-product commercialization, H₂ production was deemed unfeasible (Santana *et al.*, 2023).

Specifically for the Brazilian case, Barros Souza Riedel *et al.* (2024) demonstrated that the capacity factor, the cost of electricity, and the region where the electrolysis plant is located are sensitive factors for the levelized cost of H₂ in Brazil derived from PV and hydraulic sources, which can vary between 2.7 to 5.6 USD/kg H₂ by the year 2030.

In the case of NH₃, our analysis reported values higher than found in existing literature. However, estimated cost are in align with the conclusion that low-carbon NH₃ is currently not cost competitive at the conventional commodity (fossil) price of USD 200–300/ton NH₃ in recent years (IRENA; AEA, 2022).

Our study return a LCOA of 1,196 USD/t NH₃ which is close to the LCOA of 1,323 USD/t NH₃ for a plant with capacity of 300 t NH₃/day based on a PEM powered with onshore wind in Germany calculated by Noshervani and Neto (2021). Also, a LCOA of 1,100 EUR/t for wind-based and 900 EUR/t for PV-based NH₃ is higher than production cost for natural gas NH₃ (400 EUR/t) however, cost can decrease to 900 EUR/t (wind) and 700 EUR/t (PV) when revenues from O₂ sales are included (Vinardell *et al.*, 2023).

As stated earlier, the avoided carbon emissions are priced to enable the economic viability of green NH₃ production. Table 14 below presents the percentage of emissions avoided compared to the fossil conventional production and estimates the carbon abatement cost calculated from the difference between the LCOA of wind and PV-based NH₃ and the benchmark cost of imported fossil-based NH₃ in the Brazilian market¹⁶.

¹⁶ Price for fossil NH₃ based on the imported value of NH₃ in 2018 according to (Ministério do Desenvolvimento, Indústria, Comércio e Serviços, 2025). SH4 code - 2814

Table 14 – Abatement costs

Pathways	ΔGWP (kg CO ₂ /t NH ₃)	Cost (USD 2018/t NH ₃)	Scenario I (USD/t NH ₃)	Carbon costs (USD/t CO _{2eq})	Scenario II (USD/t NH ₃)
NH ₃ (Wind)	1,970	1,196	902.3	458.4	458.4
NH ₃ (PV)	1,690	1,908	1,614.3	955.4	955.4
NH ₃ fossil	–	293.7	-	–	-

Source: Own elaboration

In Scenario II, the avoided carbon cost equalizes the price of green NH₃ with that of fossil-based NH₃. Carbon pricing thus emerges as an effective mechanism to internalize the negative externalities of conventional NH₃ production.

Carbon cost for green NH₃ varied between 460 to 955 USD/t CO_{2eq}, which is higher than reported by Pawar *et al.* (2021) who suggest that it is necessary a carbon tax between 224 and 335 EUR/t CO₂ to make green NH₃ competitive in face of fossil NH₃ prices (275 EUR/t NH₃) due to the high cost for green NH₃ production in India, which was estimated in 744 EUR/t NH₃.

When the electricity demand required for both H₂ and NH₃ production is supplied through a PPA, the LCOH and the LCOA can be reduced by at least 23% and 54%, respectively. This reduction results from the exclusion of CAPEX associated with the construction and operation of RES. As previously discussed, CAPEX constitutes a major share of the total LCOA, meaning that when electricity is procured through a long-term PPA rather than self-generated, the overall production costs of green H₂ and NH₃ can be optimized without compromising the renewable origin of the supplied electricity.

5.3.2. Macroeconomic Analysis

The macroeconomic analysis is presented in Figures 21, 22 and 23 for the *construction* and *operation* phases of green NH₃. The only distinction between PV and wind – based NH₃ arises from the *construction* of the power plants. In the case of wind-based NH₃, the higher GDP is linked to the domestic manufacturing of wind turbine equipment, whereas PV plant equipment is fully imported.

Although PV panels are not produced domestically, the sector relies on inputs from labor-intensive activities, such as *Construction* and *Wholesale and retail trade*. In the case of NH₃ derived from a PPA supplying, all the impacts related to the *construction* phase arisen, mainly, from the H-B system since it was assumed that all the equipment and construction of this system are manufactured in Brazil.

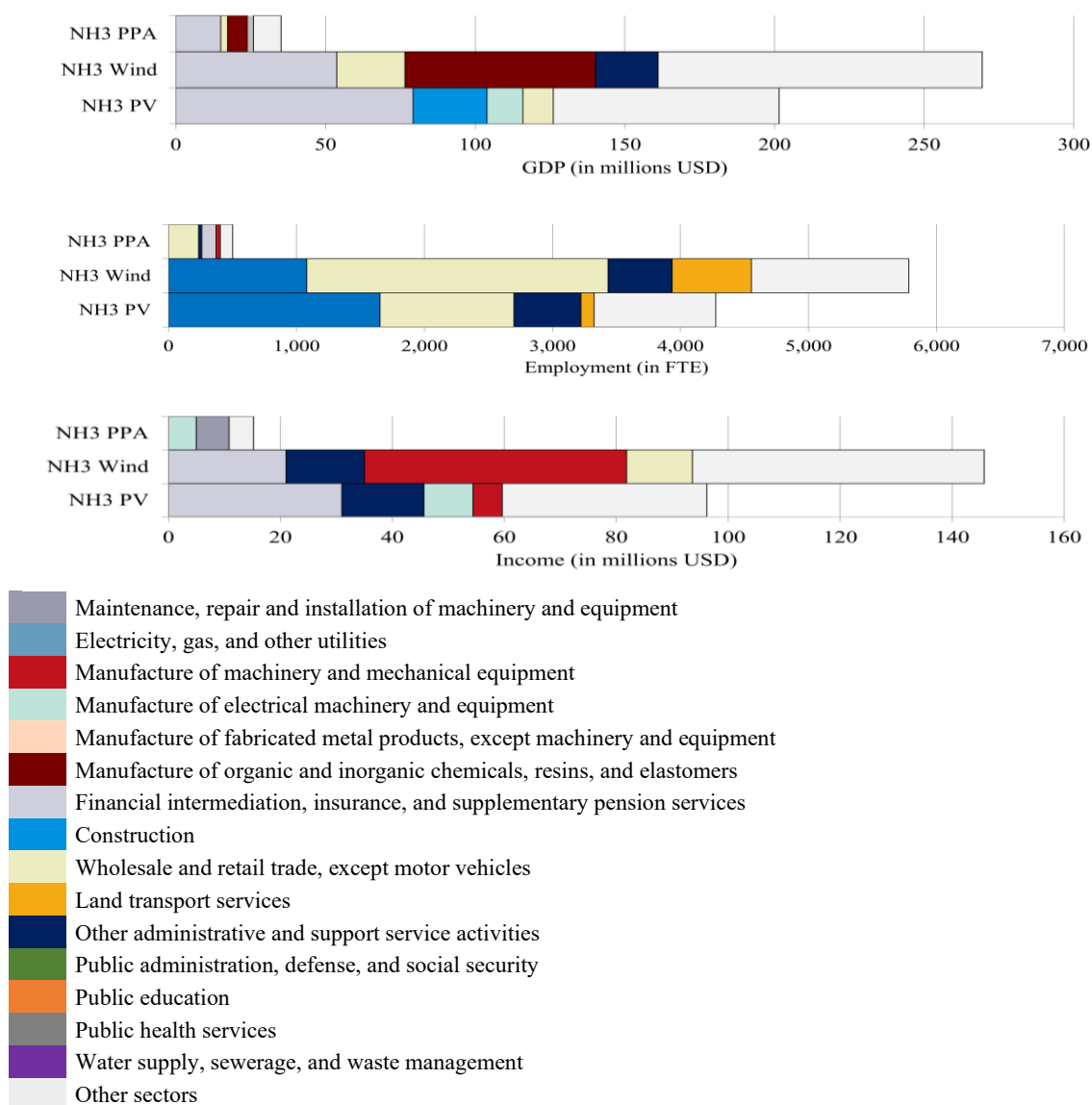


Figure 18 – Impacts attributed to the NH₃ *Construction* stage

Most of the employment generated during the NH₃ *construction* phase is associated with the *Construction* and *Wholesale and retail trade* sectors for both NH₃ derived from PV and wind electricity. Due to the high penetration of imports of PV panel in Brazilian economy, impacts attributed to PV installation are concentrated in the *Construction* sector. Similar, Araújo, Saavedra and Boeira (2023a) found that 95% of 28.3 FTE/MW employment created in PV electricity generation in Brazil is associated with the installation, operating and maintenance of PV power plants, since the manufacture of the panels occurs abroad.

In the case of wind-based NH₃, the *Wholesale and retail trade* sector is the main contributor to employment creation during the *construction* stage. Conversely, in the *operation* phase, for both Scenario I and II, positive employment effects are mainly observed in the *Electricity, natural gas, and utilities* and *Machinery maintenance* sectors. However, a significant reduction in employment is

observed in sectors with a higher concentration of Government expenditures. These sectors are labor-intensive, which explains the considerable decline in job creation resulting from the reallocation of Government subsidies toward the green NH₃ industry.

The impact on income shows that the *Mechanical equipment manufacturing* sector and the *Insurance* sectors were the most affected during the *construction* phase for wind- and PV-based NH₃, respectively.

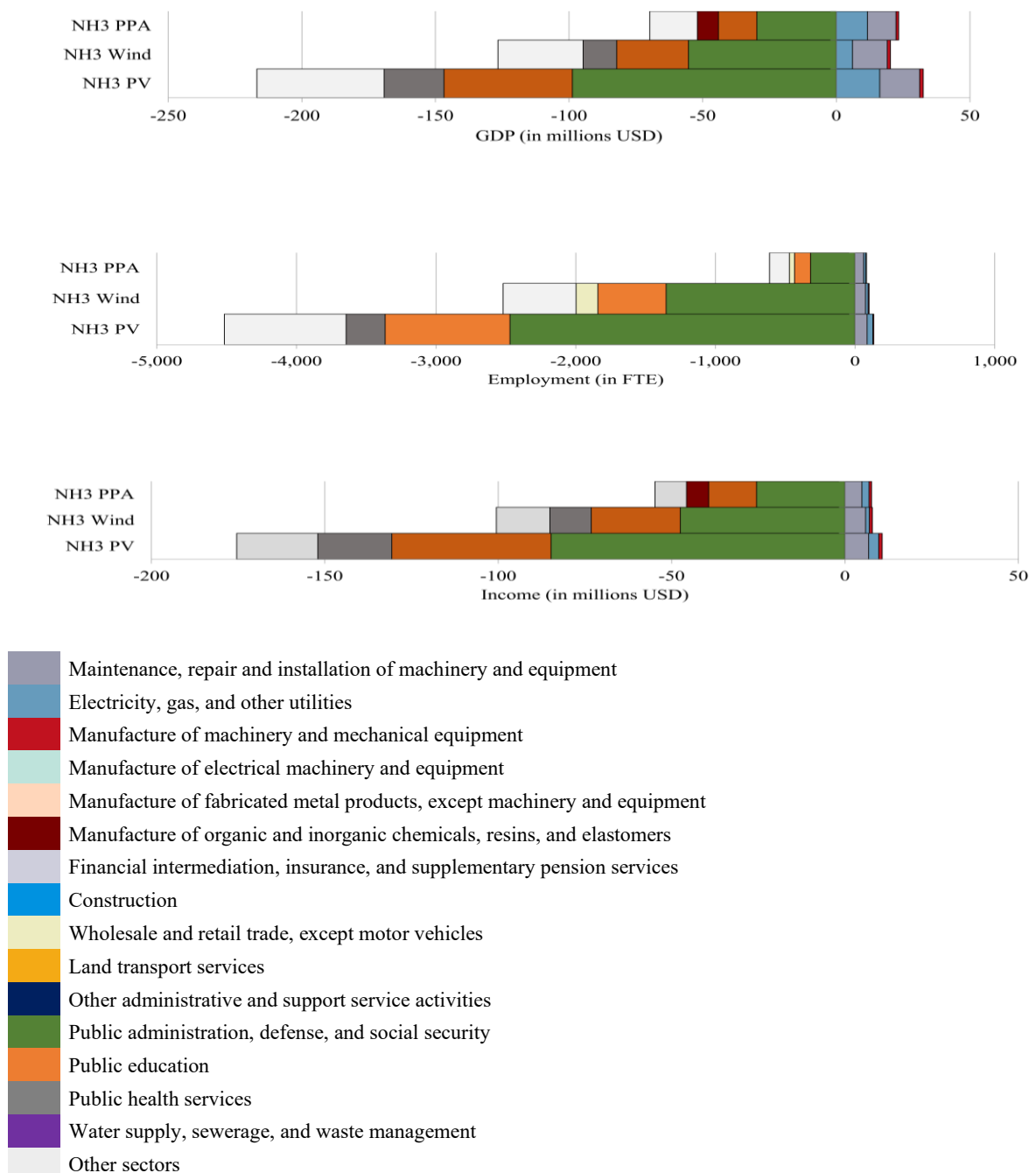


Figure 19 – Impacts attributed to NH₃ Operation stage – Scenario I

In the *operation* phase, for both Scenarios, positive sectoral impacts on GDP are dominated by

the *Electricity*, *Natural gas*, and *Maintenance* sectors, driven by activities related to the operation of wind and PV farms and the maintenance services associated with these facilities.

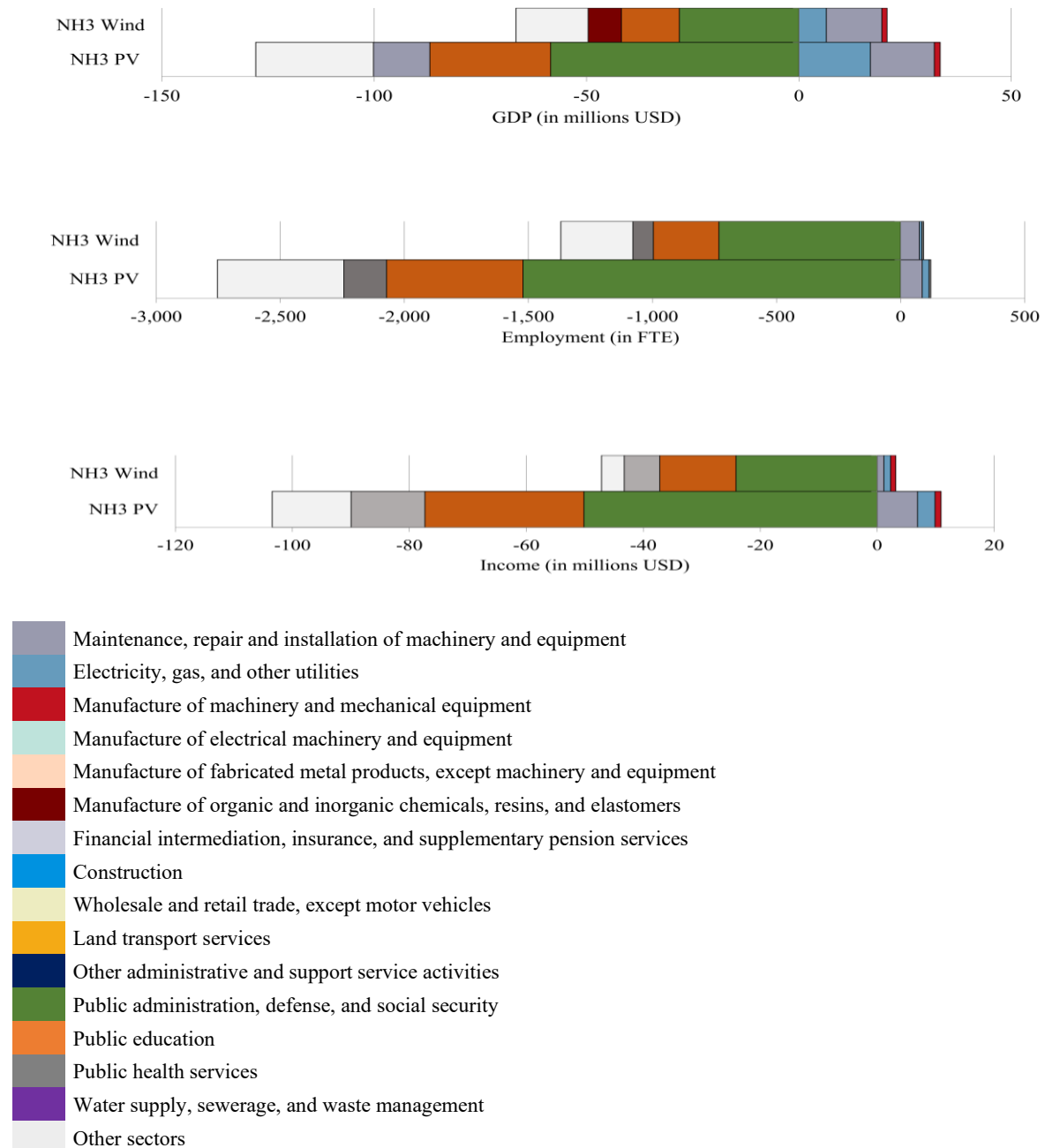


Figure 20 – Impacts attributed to NH₃ *Operation* stage – Scenario II

Source: Own elaboration

As expected, the contribution of subsidies distributed according to Government expenditures and the negative shock applied to the *Chemical* sector, in both Scenarios, resulted in negative impacts across all evaluated indicators. This outcome is primarily due to the high cost of the subsidies required to equalize the production costs of green and fossil NH₃, as well as the fact that the main government

expenditures are allocated to labor-intensive sectors with high public spending, such as *Public administration, defense, and social security, Public education, and Public health*, which together represent the largest components of government expenditures within final demand – accounting for 96% of total government spending. The results presented in this study are compared with previous literature in

Table 15, which summarizes studies that used I–O analysis to estimate the macroeconomic effects of electrolytic H₂ and NH₃ production in different contexts and regions.

Table 15 – Comparison with earlier studies

Impact indicator	H ₂		NH ₃			
	Construction	Operation	Construction	Operation		Reference
				Scenario I	Scenario II	
Contribution to GDP (M USD 2018/MW)	2.4	0.95	—	—	—	(Gupta <i>et al.</i> , 2023)
	1.2	0.03	—	—	—	(Prasad, 2024)
	1.9	0.26	9.7	0.5		(Brito, 2025)
	0.2/0.31 ¹⁷	0.07/0.18 ¹⁸	—	—	—	(Caiafa <i>et al.</i> , 2023)
	—	—	39 (PV)	- 35 (PV)	- 18 (PV)	Current study
	—	—	52 (Wind)	- 20 (Wind)	- 8.9 (Wind)	
	—	—	6.8 (PPA)	- 9.1 (PPA)		
Employment creation (FTE/MW)	15.08	5.96	—	—	—	(Gupta <i>et al.</i> , 2023)
	104	1.8	—	—	—	(Prasad, 2024)
	29	0.05	145	74.9		(Brito, 2025)
	9.3/13.7	0.003/0.008	—	—	—	(Caiafa <i>et al.</i> , 2023)
	—	—	214 (PV)	- 232 (PV)	- 131 (PV)	Current study
	—	—	289 (Wind)	- 132 (Wind)	- 6.4 (Wind)	
	—	—	25 (PPA)	- 9.9 (PPA)		
GHG Emissions (kg CO ₂ e/kg NH ₃)	0.05	0.4	—	—	—	(Gupta <i>et al.</i> , 2023)
	2.7	0.19	—	—	—	(Prasad, 2024)
	1.6	0.45	0.2	0.14		(Brito, 2025)
	—	—	0.2 (Wind)	—	—	Current study
			0.48 (PV)	—	—	

¹⁷ H₂ Wind/H₂ PV

¹⁸ H₂ Wind/H₂ PV

The results of this study may be partially influenced by the high share of imported technologies in the assessed scenarios. Since the electrolyzers and PV panels are predominantly manufactured abroad, the environmental and economic profiles of these technologies reflect foreign production chains rather than domestic conditions. Promoting a local supply chain for these components is therefore fundamental, as it could substantially alter the life cycle results and improve Brazilian trade balance by reducing dependence on imported technology.

In this way, Caiafa *et al.* (2023) applied an I–O framework to a 2 GW green H₂ plant in Ceará, Brazil, assuming all core technologies (electrolysis, wind, PV manufacturing) are imported and only construction expenditures utilize local inputs. They estimated operational value-added of USD 155 million and income of approximately USD 173 million during construction, highlighting the limited economic benefits when technology and equipment are not sourced domestically.

Similar to this work, Gupta *et al.* (2023) applied an I–O approach to assess the use of H₂ derived from hydropower to replace fossil diesel in Switzerland. Their results showed that such substitution could increase job creation by 163% and reduce GHG emissions by 45%, assuming that all electrolysis components were manufactured domestically. In contrast, the present study demonstrated that, although replacing fossil NH₃ with green one could lead to significant emission reductions, the high production cost of green NH₃ still prevents the consolidation of this industry in Brazil, given the negative macroeconomic impacts observed under the current cost structure.

Prasad (2024), by applying an I–O framework for 1 GW of green H₂ in India, estimated GDP gains of 72,334 million USD and 6.31 million jobs, mostly from construction, but showed that full import dependence could reduce these effects by 65% (GDP) and 55% (jobs). In line with this, the present study assumes partial import dependence for NH₃ CAPEX (63% for PV and 19% for wind), which significantly reduces the estimated macroeconomic indicators for Brazil.

Macroeconomics effects associated with electrolytic NH₃ industry in Brazil were reported by Brito (2025) who used the 2018 I–O matrix Brazilian for estimating impacts on GDP, employment creation, value added and average wage attribute to an industry of green NH₃ production with capacity of 600 t NH₃/day. The analysis conducted has not considered the construction and operation of wind and PV power stations, which were included in our study. In this sense, Brito (2025) reported a strong dependence electricity section on itself because the disaggregation of electricity sector into its components (generation, transmission and distribution as well as by energy type – solar, wind, biomass, nuclear) was not carried out.

Despite assuming partial import of NH₃ production machinery, our construction-phase results show a fourfold higher GDP and 1.4-fold higher job creation compared to Brito (2025), who assumed all machinery was domestic manufactured. This can be attributed to the inclusion of CAPEX for PV and wind power system. Brito also noted that 90% of green NH₃ subsidies aim to equalize its cost with fossil

NH₃, though the subsidy source was unspecified.

Martins *et al.* (2024) applied I–O analysis to green H₂ from ethanol reforming in Brazil (1 MW of capacity H₂ installed), estimating GDP and employment multipliers of 1.5 and 1.4, with gross impacts of BRL 28,010/MW and 0.4579 FTE jobs/MW. The study concluded that while economic benefits are moderate, investments and scaling are needed and emphasized the key role of agriculture in labor absorption.

Brazilian fertilizer sector can deliver high return in economy as demonstrated by Castro, Silva and Gilio (2021) who showed that each BRL 1.0 spend in the fertilizer sector, a return of BRL 2.2 can be created and for each BRL 1.0 of income generated in fertilizer sector three more times income is generated in economy, by considering direct and indirect effects.

The results of the macroeconomic analysis (for both Scenario I and II) showed that government-funded subsidies aimed at promoting a green NH₃ industry generate negative outcomes across all evaluated indicators. The assumed distribution of government spending, used as a reference for subsidizing green NH₃ production, may be an unrealistic simplification, as funds that are usually assigned to public health and education may be redirected to support the NH₃ industry instead. In this context, alternative forms of financing and subsidy mechanisms must be looked for.

Consequently, the identification of alternative funding mechanisms is essential to enhance the economic competitiveness of green NH₃. From an environmental perspective, green NH₃ production has the potential to reduce carbon emissions by up to 90% compared to its fossil counterpart. Therefore, mechanisms capable of redistributing the subsidy burden to sectors with higher capacity to absorb cost increases – without significant pass-through effects to end consumers – should be prioritized. Potential approaches include imposing tariffs on fossil NH₃ imports or implementing a green tax on the chemical industry, thereby generating dedicated revenue streams to support the development of a domestic green NH₃ industry.

Although contracting electricity through PPAs can significantly reduce the LCOH and LCOA by excluding CAPEX associated with power generation, the choice between self-generation and long-term PPAs involves strategic tradeoffs. Auto production offers greater operational control, energy security, and traceability of renewable origin – essential for low-carbon certification – while PPAs provide capital efficiency and cost predictability. Therefore, the choice depends on the investor's financial structure, risk tolerance, and long-term integration strategy within the green H₂ and NH₃ value chain.

Although the negative impacts in Scenario II are smaller than those in Scenario I, the cost of

avoided carbon remains high. Current CBIO¹⁹ prices traded on the Brazilian stock exchange in 2025 average around BRL 60 – 70 per unit (B3, 2025), representing costs much lower than those estimated to equalize the price of green NH₃ with that of fossil NH₃ produced in the country.

Electrolytic NH₃ may become competitive under scenarios of improved energy efficiency, large-scale deployment of electrolyzers, and the implementation of carbon pricing (Noshervani; Neto, 2021). At present, however, it cannot match fossil-based NH₃ in terms of production costs and economies of scale, which hinders its market establishment. Nevertheless, reducing external dependence on fossil fuels and imported agricultural inputs such as NH₃, while simultaneously consolidating a domestic green H₂ and NH₃ industry, could position Brazil as a key player in producing commodities derived from renewable energy resources.

The country's availability of renewable energy sources – currently accounting for 88% in 2024 (EPE, 2025) of its power mix – highlights its potential to produce low – carbon energy and chemical inputs, while also fostering the development of a high – tech, digitally oriented industry.

The cost of renewable electricity has decreased in recent years (IRENA, 2023). Electricity cost is a critical factor for the economics of green H₂ and its derivatives, as it represents a significant share of total production costs – reaching up to 60% of the total cost of H₂ (Pinheiro *et al.*, 2025).

Future research should explore alternative sources of revenue to reduce the production cost of a green NH₃ industry in Brazil. Subsidies for renewable energy industries remain modest both globally and domestically, yet they are crucial in the early stages of developing new industries characterized by high installation costs and low technological readiness levels (TRL). Subsidies for fossil resources still predominate in Brazil. In 2023, fossil fuel subsidies totaled USD 16.34 billion – representing 81.9% of total energy subsidies – while support for renewables reached only USD 3.61 billion (INESC, 2024).

In this context, resources derived from fossil activities – such as carbon taxation, royalties from fossil energy exploration, or tariffs on fossil energy imports – could be redirected to support the development of a green H₂ and NH₃ industry in the country. In order to decrease green NH₃ cost and enhance its competitive it is necessary to incorporate the cost of avoided carbon for electrolytic NH₃ (Mohamed; Economou; Bicer, 2024).

In addition to the challenges previously outlined, the absence of a robust supply chain capable of delivering the inputs required for electrolytic NH₃ production is still a critical barrier. The domestic manufacturing capacity for essential components – such as PV panels and electrolyzers – still limited, both in availability and in the scale necessary to support the production volumes assessed in this study.

Caiafa *et al.* (2023) and Prasad (2024) showed that employment creation and impacts on GDP

¹⁹ Decarbonization Credit (CBIO) was created as an instrument of the RenovaBio Program and is registered in book-entry form to verify the individual target compliance of fuel distributors, as established in Article 7 of Law No. 13,576/2017. An environmental asset whose trading has been allowed on the Brazilian Stock Exchange (B3) since December 2019 (MME, 2025). One CBIO is equivalent to 1t of carbon avoided.

can be enhanced in the scenarios where all the CAPEX is sourced domestically. Specifically to Brazil, impacts on GDP and employment can increase in 95% and 92%, respectively, when is considered that all the CAPEX for H₂ production based on wind and PV comes from national industries (Caiafa *et al.*, 2023).

Consequently, Brazil must not only reduce its dependence on imported energy resources such as NH₃ but also develop a technologically advanced industrial base capable of supplying all components necessary for green NH₃ synthesis. Lessons learned from the wind energy sector – where governmental incentives were pivotal in structuring and consolidating a domestic wind turbine industry – could be effectively leveraged to accelerate the establishment of a competitive H₂ and renewable NH₃ value chain.

Reducing the production cost of H₂ is fundamental to ensuring a competitive cost for green NH₃. Investment costs are a significant share of the LCOH and LCOA. In this regard, technological progress, cost reductions in equipment manufacturing, and efficiency improvements can substantially decrease the initial capital investment needed for green NH₃ plants. Future cost declines are also expected to result from economies of scale and learning effects, as the deployment of electrolyzers and renewable energy systems expands globally.

The feasibility of green NH₃ and the reduction of its production cost can also be achieved through the integration of PV and wind power plants operating in a complementary manner. This configuration ensures a high-capacity factor for NH₃ production while reducing dependence on battery and H₂ storage systems. In this integrated scenario, the cost ranges between USD 532 – 716/t NH₃ depending on the share of PV and wind (Palys; Daoutidis, 2023).

PEM electrolyzer assessed in this work has a power capacity of 177 MW and H-B, only 20 MW, which can increase the CAPEX of those systems and reduce the delivery of commodities. However, it is important to mention that only few PEM systems with higher power capacity are available. The large – scale PEM that are being operated has a sizes up to 20 MW, however, it is expected in the period towards 2025 – 2030 several large – scale plants in the range up to 1 GW are either in a feasibility study stage or in planning phase (Reksten *et al.*, 2022). Yet, it not still possible to achieve the capacity production of green NH₃ compare to conventional methods that are capable of 1,500 t NH₃/year (Noshervani; Neto, 2021).

It is expected that distinct NH₃ markets may develop, facilitated by certification schemes, contracts for difference, and other mechanisms (IRENA; AEA, 2022). As discussed above, NH₃ has been identified as an alternative carrier for transporting the energy contained in H₂. However, additional costs are needed to enable the long-distance transport of NH₃ in its liquid form.

Also, future studies could employ a computable general equilibrium (CGE) model that would be required to evaluate the impacts of financing the subsidy through the fossil NH₃ or non-green fertilizer sectors. According to Nicolella, Dragone and Bacha (2005) and Ogino *et al.* (2021), Fertilizer sector in Brazil is highly inelastic demands in other words, any cost would be passed on to prices, which

makes the I-O framework unsuitable for this exercise.

6 CONCLUSIONS

This study provided a comprehensive assessment of hydrogen supply chains in Brazil, analyzing multiple production pathways in terms of carbon emissions, fossil fuel dependency, and water consumption, as well as the macroeconomic implications of using hydrogen for green ammonia production. A harmonized Life Cycle Assessment (LCA) approach was applied to seven H₂ production routes: water electrolysis powered by wind energy, photovoltaic systems, and the Brazilian power grid; and steam reforming of natural gas, sugarcane ethanol, corn ethanol, and landfill biogas.

From an environmental standpoint, renewable-based routes presented relevant trade-offs throughout their life cycle. Although electrolysis powered by wind or PV generally reduced greenhouse gas emissions, in some cases these routes performed worse than conventional steam methane reforming when individual indicators were considered. Overall, renewable energy systems, whether *ongrid* or *offgrid*, achieved GHG reductions of 15–96% and energy performance improvements of 2–30-fold compared to SMR. Conversely, alkaline electrolysis (AEL) off-grid systems showed up to a 150-fold increase in water impacts, mainly due to water consumption embedded in battery manufacturing. Biomass-based routes (corn or sugarcane ethanol) achieved up to 80% carbon reduction and fossil energy requirements of 14–20 MJ/kg H₂, but their Water Scarcity Footprint (WSF) was 7.2–15.5 times higher than SMR.

Tradeoff analysis confirmed that no single pathway dominates across all indicators. Still, SRBio and *ongrid* wind electrolysis stood out as the most balanced options. SRBio delivered the highest Fossil Energy Ratio (59.3) and low water use (50 L/kg H₂), although its Global Warming Potential (4.1 kg CO₂e/kg H₂) was moderately affected by methane leakage during biogas purification. Wind-based electrolysis achieved the lowest GWP (96% reduction vs. SMR) and a strong FER (18.2) but exhibited a twofold higher WSF than SMR due to regional water scarcity. In contrast, grid-connected AEL relying on the Brazilian marginal mix showed the weakest performance, with the highest emissions, lowest FER, and no advantage in water use.

To reduce Brazilian dependence on fossil-based ammonia, the study also evaluated the macroeconomic impacts of replacing conventional ammonia with green NH₃ derived from wind and PV electricity. The levelized cost of green ammonia ranged from 778.2 to 1,908 USD/t NH₃, up to 80% higher than fossil-based NH₃ and approximately 62% above current national production costs. Two subsidy scenarios were examined: one based on the direct cost gap between green and fossil ammonia, and another based on avoided carbon emissions from substituting conventional NH₃.

Input–Output analysis showed that allocating subsidies through direct government spending leads to concentrated negative macroeconomic effects, particularly in sectors with higher public expenditure (e.g., health, education, and administrative services). When subsidies were linked to avoided emissions, these negative effects persisted but were less severe. Environmentally, green NH₃ can cut emissions by up to 90% relative to fossil ammonia, suggesting that part of these avoided emissions could

be monetized to finance the transition and partially offset the economic drawbacks.

Therefore, relying solely on public spending for subsidies is not viable. Future strategies should diversify funding sources, including carbon taxation, royalties from fossil energy exploration, and import tariffs on fossil-based products. In parallel, industrial policies should target domestic manufacturing of key components, such as PEM electrolyzers and PV panels, which are currently imported. Localizing these technologies could reduce levelized production costs and enhance socioeconomic benefits in employment, income, and value added. Together, these measures would strengthen Brazilian position in the global green hydrogen and ammonia markets, aligning economic competitiveness with environmental benefits.

APPENDIX

Table A16 – GWP of H₂ production

Route	GWP (kg CO ₂ e/kg H ₂)	Location of the study	Observations	Boundaries	Ref.
SMR	11.2	–	–	Cradle-to-gate	(Hajjaji <i>et al.</i> , 2013)
	11.9	–	–	Not specified	(Suleman; Dincer; Agelin-Chaab, 2016)
	13.8	–	–	Well-to-pump	(Siddiqui; Dincer, 2019)
	9.8	–	–	Cradle-to-use	(Hacatoglu; Rosen; Dincer, 2012)
	10.8	Europe	–	Cradle-to-gate	(Antonini <i>et al.</i> , 2020)
	10.2	–	–	Cradle-to-grave	(Sadeghi; Ghandehariun; Rosen, 2020)
	10.4	–	–	Cradle-to-gate	(Henriksen <i>et al.</i> , 2023)
	7	–	–	Cradle-to-gate	(Hren <i>et al.</i> , 2023)
	12.6	–	–	Cradle-to-gate	(Mio <i>et al.</i> , 2024)
	8.0	–	–	Well-to-pump	(Dong <i>et al.</i> , 2016)
	12.3	Finland	–	Cradle-to-gate	(Patel <i>et al.</i> , 2024)
CGR	23.7	–	–	Well-to-pump	(Siddiqui; Dincer, 2019)
	11.59	Iran	–	Cradle-to-grave	(Sadeghi; Ghandehariun; Rosen, 2020)
	24.2	–	–	Cradle-to-grave	(Mehmeti <i>et al.</i> , 2018)
	26	–	–	Cradle-to-gate	(Simons; Bauer, 2011)
	51.86	–	–	Cradle-to-distribution	(Li <i>et al.</i> , 2020)
	84.2	–	–	Not specified	(Sanchez <i>et al.</i> , 2020)
	14.74	–	–	Cradle-to-gate	(Liu; Liu, 2021)
SRBio	9.2	Swedish	Wheat grains EtOH	Cradle-to-gate	(Hajjaji <i>et al.</i> , 2013)
	6.8	–	–	Cradle-to-gate	(Hajjaji <i>et al.</i> , 2016b)
	7.27	Tunisian	Sugar beet EtOH	Cradle-to-gate	(Khila <i>et al.</i> , 2016)
	10.8	–	AD of organic waste	Cradle-to-gate	(Martínez– Ramón <i>et al.</i> , 2024)
	0.25	Germany	Biogas supply	Cradle-to-gate	(Battista <i>et al.</i> , 2017)
	12.2	United States	Corn EtOH	Well-to-pump	(Siddiqui; Dincer, 2019)
	–4.8	Europe	AD of waste	Cradle-to-gate	(Antonini <i>et al.</i> , 2020)
	4	–	Waste corn crops and pig manure AD manure, cheese whey, maize silage and fodder beet	Cradle-to-distribution	(Hren <i>et al.</i> , 2023)
	5.6	–	–	Cradle-to-gate	(Hajjaji <i>et al.</i> , 2016b)
	10	United States	Biomass collection	Well-to-pump	(Siddiqui; Dincer, 2019)
	3.9	South Korea	Landfill gas	Well-to-wheel	(Yoo; Kim; Song, 2018)
	2.13	Sweden	Mostly food waste	Cradle-to-gate	(Arfan <i>et al.</i> , 2023)
	–31,8	–	Residues from landfill bioreactor	Cradle-to-gate	(Wijayasekera <i>et al.</i> , 2022)

Route	GWP (kg CO ₂ e/kg H ₂)	Location of the study	Observations	Boundaries	Ref.
EL	23	Italy	AEL Grid mix	Cradle-to-gate	(Mio <i>et al.</i> , 2024)
	28.01	–	AEL Grid 80% fossil	Cradle-to-gate	(Dufour <i>et al.</i> , 2012)
	6.3	Brazil	Grid	Cradle-to-gate	(Santana <i>et al.</i> , 2023)
	28.6	United States	Grid	Well-to-pump	(Siddiqui; Dincer, 2019)
	31	United States	PEM Grid	Cradle-to-gate	(Henriksen <i>et al.</i> , 2023)
	23	Union Europe	Grid 2019	Cradle-to-distribution	(Hren <i>et al.</i> , 2023)
	5.7	–	AEL PV	Cradle-to-gate	(Dufour <i>et al.</i> , 2012)
	2.0	Canada	PV	Cradle-to-grave	(Cetinkaya; Dincer; Naterer, 2012)
	0.37	–	PV	Not specified	(Suleman; Dincer; Agelin-Chaab, 2016)
	3.1	Iran	PV AEL	Cradle-to-grave	(Sadeghi; Ghandehariun; Rosen, 2020)
	2.8	–	PEM PV	Cradle-to-gate	(Henriksen <i>et al.</i> , 2023)
	0.5	Switzerland	AEL PV	Cradle-to-gate	(Simons; Bauer, 2011)
	2.5	Finland	PEM PV	Cradle-to-gate	(Patel <i>et al.</i> , 2024)
	2.5	Australia	AEL PV	Cradle-to-gate	(Palmer <i>et al.</i> , 2021)
	1.9	Germany	Wind	Cradle-to-grave	(Burkhardt <i>et al.</i> , 2016)
	0.7	Canada	Wind	Cradle-to-distribution	(Ghandehariun; Kumar, 2016)
	9.7	–	Wind	Cradle-to-gate	(Hren <i>et al.</i> , 2023)
	0.4	Europe	AEL Wind	Well-to-tank	(Simons; Bauer, 2011)
	3.4	–	Wind	Cradle-to-gate	(Dufour <i>et al.</i> , 2012)
	0.9	Canada	Wind	Cradle-to-gate	(Cetinkaya; Dincer; Naterer, 2012)
	0.0325	–	Wind	Not specified	(Suleman; Dincer; Agelin-Chaab, 2016)
	1.8	–	PEM Wind	Cradle-to-gate	(Henriksen <i>et al.</i> , 2023)
	0.6	Finland	PEM Wind	Cradle-to-gate	(Patel <i>et al.</i> , 2024)

Table A17 – WC and WSF of H₂ production

Route	Location of the study	Observations	Method	WC L H ₂ O/kg H ₂	WSF m ³ H ₂ O/kg H ₂	Ref.
SMR	United States	–	LCA	15.8	–	(Deo; Setoyama; Sieving, 2022)
	United States	–	LCA	11.7	–	(Lampert <i>et al.</i> , 2015)
	–	–	AWARE	5.77	247.5	(Mehmeti <i>et al.</i> , 2018)
	–	–	WFN	52.4	–	(Olaitan; Bertagni; Porporato, 2024)
	Brazil	–	LCA	257	–	(De Souza <i>et al.</i> , 2021)
CG	United States	–	LCA	20.8	–	(Deo; Setoyama; Sieving, 2022)
	–	–	AWARE	13.1	570.2	(Mehmeti <i>et al.</i> , 2018)

Route	Location of the study	Observations	Method	WC L H ₂ O/kg H ₂	WSF m ³ H ₂ O/kg H ₂	Ref.
						2018)
	United States	–	LCA	28	–	(Henriksen <i>et al.</i> , 2023)
		–	WFN	80	–	(Olaitan; Bertagni; Porporato, 2024)
	China	–	LCA	127.2	–	(Cui <i>et al.</i> , 2021)
SREtOH	Brazil	Maize ethanol	AWARE	2.24	91.61	(Mehmeti <i>et al.</i> , 2018)
		Wheat ethanol		3.87	149.4	(Mehmeti <i>et al.</i> , 2018)
		Sugarcane ethanol	LCA	9,600	–	(De Souza <i>et al.</i> , 2021)
BG	United States	Waste corn crop	AWARE	4.94	212.4	(Mehmeti <i>et al.</i> , 2018)
		–	LCA	532		(Henriksen <i>et al.</i> , 2023)
		–	WFN	7,467		(Olaitan; Bertagni; Porporato, 2024)
BP	China	Wheat straw biomass	LCA	9,332.40	–	(Cui <i>et al.</i> , 2021)
EL		PV		29	–	(Olaitan; Bertagni; Porporato, 2024)
		Wind	WFN	9.2	–	(Olaitan; Bertagni; Porporato, 2024)
		Nuclear		105	–	(Olaitan; Bertagni; Porporato, 2024)
	United States	PV/PEM	LCA	15.5	–	(Deo; Setoyama; Sieving, 2022)
	United States	Wind/PEM	LCA	15.5	–	(Deo; Setoyama; Sieving, 2022)
		Grid not specified/PEM	AWARE	223.4	9,604.30	(Mehmeti <i>et al.</i> , 2018)
		Grid not specified /SOEC	AWARE	146.8	6,312.30	(Mehmeti <i>et al.</i> , 2018)
		Wind/SOEC	AWARE	9	379.3	(Mehmeti <i>et al.</i> , 2018)
		Wind/PEM	AWARE	16.40	629.8	(Mehmeti <i>et al.</i> , 2018)
	United States	Grid/PEM	LCA	280	–	(Henriksen <i>et al.</i> , 2023)
	United States	PV/PEM	LCA	40	–	(Henriksen <i>et al.</i> , 2023)
	United States	Wind/PEM	LCA	26	–	(Henriksen <i>et al.</i> , 2023)
	United States	Grid/PEM	LCA	220	–	(Henriksen <i>et al.</i> , 2023)
	United States	PV/SOEC	LCA	26	–	(Henriksen <i>et al.</i> , 2023)
	United States	Wind/SOEC	LCA	25	–	(Henriksen <i>et al.</i> , 2023)

Route	Location of the study	Observations	Method	WC L H ₂ O/kg H ₂	WSF m ³ H ₂ O/kg H ₂	Ref.
	Australia	Grid/PEM	AWARE	200	3.0	(Shi; Liao; Li, 2020)
	Australia	PV/PEM	AWARE	40	1.0	(Shi; Liao; Li, 2020)
	Australia	Wind/PEM	AWARE	20	0.4	(Shi; Liao; Li, 2020)
	China	PV/AEL	AWARE	66.6	915	(Du <i>et al.</i> , 2024)
	China	Wind/AEL	AWARE	36.4	1,700	(Du <i>et al.</i> , 2024)
	United States	Wind/AEL	LCA	30.2	–	(Lampert <i>et al.</i> , 2015)
	United States	PV/AEL	LCA	30.2	–	(Lampert <i>et al.</i> , 2015)

Table A18 – CED and EI of H₂ production

Route	CED (MJ/kg H ₂)	EI	References
SMR	216	0.6*	(Simons; Bauer, 2011)
	–	2.44	(Mio <i>et al.</i> , 2023)
	–	5.5	(Mio <i>et al.</i> , 2024)
CG	300	0.4*	(Simons; Bauer, 2011)
	162	0.7*	(Liu; Liu, 2021)
	100	1.2	(Liu; Liu, 2021)
	–	1.47	(Mio <i>et al.</i> , 2023)
	450	0.25*	(Liu <i>et al.</i> , 2023)
	350	0.3*	(Liu <i>et al.</i> , 2023)
SRBio	164	0.7*	(Cvetković <i>et al.</i> , 2021)
	–	12.0	(Hajjaji <i>et al.</i> , 2016a)
BG	117.4	1.02	(Li <i>et al.</i> , 2020)
EL PV	60	2.0*	(Simons; Bauer, 2011)
	–	4.6	(Palmer <i>et al.</i> , 2021)
	–	7.22	(Mio <i>et al.</i> , 2023)
	62	2.0*	(Dufour <i>et al.</i> , 2012)
	–	13.4	(Mio <i>et al.</i> , 2024)
	30	4.0*	(Simons; Bauer, 2011)
	34	4.1*	(Burkhardt <i>et al.</i> , 2016)
EL Grid EU	341	0.4*	(Dufour <i>et al.</i> , 2012)
EL Grid (45% NG and 20% Hydro)	–	14.3	(Mio <i>et al.</i> , 2024)

*Estimated by the authors based on LHV H₂ (EI = LHV H₂/CED_{fossil})

- LCI for H₂ production Systems

Table A19 – Physical proprieties of fuels and substances

Fuel/product	Density [kg/m ³]	LVH [MJ/kg]	HHV [MJ/kg]	Reference
Alcohol hydrated	809.0	26.0	–	(EPE, 2023a)
Alcohol anhydrous	791.0	28.0	–	(EPE, 2023a)
Vinasse	873.0	0.5	–	(Ocampo Batlle <i>et al.</i> , 2021)
Diesel A	840.0	42.3	–	(ANP, 2024)
Biodiesel (B100)	880.0	37.6	–	(EPE, 2023a)
Natural gas (average)	0.8	48.5	–	(Spath; Mann, 2001)
Biogas (60% Methane)	1.2	17.6	–	(Argalis; Vegere, 2021)
Biomethane (96% Methane)	0.8	45.3	–	(Carvalho <i>et al.</i> , 2023)
Hydrogen (25 °C and 1 bar)	0.1	120.0	140.0	(Spath; Mann, 2001)
Water (25 °C)	997.0	–	–	(ANP, 2024)
Oil	884.0	45.2	–	(ANP, 2024)
DDGS – Dried distillers’ grains with soluble	–	20.2	–	(ANP, 2024)
CGF – Corn gluten feed	–	18.6	–	(ANP, 2024)
Maize oil	–	37.2	–	(ANP, 2024)
Soybean oil	–	34.0	–	(ANP, 2024)
Soybean meal	–	15.4	–	(ANP, 2024)
Glycerin	–	16.2	–	(ANP, 2024)
Crude glycerin	–	14.6	–	(ANP, 2024)
Electricity (MWh)	–	–	–	3.6 MJ

- LCI Steam Methane Reforming Natural Gas

Table A20 – SMR of natural gas system description²⁰

Parameter	Value	Unit
Hydrogen production rate	5.0E+03	kg H ₂ /h
Full load hours	7.5E+03	h/year
Lifetime operation	2.0E+01	year
Total H ₂ production over lifetime	7.5E+08	kg
Natural gas consumption (as feedstock)	1.4E+02	MJ/kg H ₂

²⁰ Based on (Spath; Mann, 2001; Wulf; Kaltschmitt, 2018)

Natural gas consumption (as fuel)	1.5E+01	MJ/kg H ₂
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Table A21 – LCI for SMR operation and construction stages

Inputs	Value	Unit	Process
Electricity	3.2E–01	kWh	From Brazilian Grid – Table A66
Natural gas as feedstock	1.4E+02	MJ	From Natural Gas production and Transportation in Brazil
Natural gas for steam	1.5E+01	kg	Steam in chemical industry ²¹
Electricity for compression	1.2E+00	kWh	Water, deionised {RoW} water production, deionised
Tap water	1.6E+01	kg	Tap water {BR} tap water production, conventional treatment. For steam production (13.3 kg) and cooling system (2.38 kg)
Outputs	Value	Unit	Process
H ₂	1.0E+00	kg	–
Construction materials	Value	Unit	Process
Steel, low alloy	1.0E+02	t	Steel, low–alloyed {GLO} market for steel, low–alloyed
Steel, high alloy	6.0E+01	t	Steel, chromium steel 18/8 {GLO} market for steel, chromium steel 18/8
Steel, no alloy	2.4E+02	t	Steel, unalloyed {GLO} market for steel, unalloyed
Zinc	3.0E–01	t	Zinc {GLO} market for zinc
Aluminum	3.5E+00	t	Aluminum, primary, ingot {GLO} market for
Nickel	3.0E–01	t	Iron–nickel–chromium alloy {RoW} iron–nickel–chromium alloy production
Copper	1.0E–01	t	Copper {RoW} copper production, primary
Concrete	1.3E+03	t	Concrete block {BR} concrete block production
Outputs	Value	Unit	Process
H ₂ factory	1.0E+00	unit	–
Emissions air ²²	Value	Unit	Process
CO ₂ , fossil	8.9E+00	kg/kg H ₂	(Wulf; Kaltschmitt, 2018)
CH ₄ , fossil	0.0E+00	kg/kg H ₂	

²¹ It was adapted to Brazil conditions.

Tap water, electricity and natural gas consumption are assumed to be the closest proxy available. Steam's low heat value is 2.75 MJ/kg.

²² Emissions due natural gas burnt for heating process

Table A22 – Natural Gas production and transport in Brazil

Output	Value	Unit	Process
Natural Gas ²³	1.00E+00	m ³	–
Inputs	Value	Unit	Process
Liquefied Natural Gas (LPG)	6.3E–02	m ³	Natural gas, liquefied {RoW} natural gas production, liquefied
National production onshore	1.4E–01	m ³	Natural gas, high pressure {BR} petroleum and gas production, onshore
National production offshore	6.6E–01	m ³	Natural gas, high pressure {BR} petroleum and gas production, offshore
International production onshore	1.3E–01	m ³	Natural gas, high pressure {BR} natural gas, high pressure, import from BO
LPG transportation	3.3E–01	tkm	Transport, freight, sea, liquefied natural gas {GLO} market for. Average distance of 7100 km from the three major exporters: Nigeria, Catar and Trinidad&Tobago
On–shore transportation from imported share	1.8E–01	tkm	Transport, pipeline, onshore, long distance, natural gas {GLO} market for. Transportation of imported share through GASBOL (Bolivia–Brazil): 1,700km.
On–shore transportation from national share	1.5E+00	tkm	Transport, pipeline, onshore, long distance, natural gas {GLO} market for. Transportation of national share (Fortaleza–São Paulo): 3,000 km.
Off–shore transportation	2.9E–02	tkm	Transport, pipeline, long distance, natural gas {DZ} market for. Transportation of national share (Santos’s Basin – São Paulo): 300 km

- Steam Reforming Biomethane

Table A23 – Steam Biomethane Reforming system description²⁴

Parameter	Value	Unit
Hydrogen production rate	5.0E+03	kg H ₂ /h
Full load hours	7.5E+03	h/year
Lifetime operation	2.0E+01	year

²³ Natural gas market share in Brazil. Data from (ANP, 2023). Average values 2017 - 2022

²⁴ It was assumed the same system operational as SMR described in Table A20

Total H ₂ production over lifetime	7.5E+08	kg
Biomethane (as feedstock)	1.4E+02	MJ/kg H ₂
Biomethane (as fuel)	1.5E+01	MJ/kg H ₂
Hydrogen production rate	5.0E+03	kg H ₂ /h

Table A24 – Steam landfill biomethane reforming

Inputs	Value	Unit	Observation
Biomethane (as feedstock)	1.4E+02	MJ	Calculated based on LHV of biomethane
Biomethane (fuel)	1.5E+01	MJ	Heat, district or industrial {BR} heat production, biomethane. Steam LHV 2.75 MJ/kg. It was assumed that steam is supplied by landfill biomethane.
Tap water	1.6E+01	kg	Tap water {BR} tap water production, conventional treatment. For steam production (13.3 kg) and cooling system (2.38 kg)
Electricity	2.0E-01	kWh	From Brazilian Grid
Electricity for compression	1.2E+00	kWh	From Brazilian Grid
Output	Value	Unit	Observation
H ₂	1.0E+00	kg	Output pressure 200 bar
Emissions air	Value	Unit	Observation
CO ₂ , biogenic	5.4E+00	kg ²⁵	
CH ₄ , biogenic	6.7E-02	kg ²⁶	

- LCI Steam Reforming Ethanol

Table A25 – Steam Ethanol Reforming system description²⁷

Parameter	Value	Unit
Hydrogen production rate	6.3E+01	kg H ₂ /h
Full load hours	7.5E+03	h/year
Lifetime operation	2.0E+01	year

²⁵ Based on (Ecoinvent, 2023; Ingale *et al.*, 2022)

²⁶ Based on (Ecoinvent, 2023; Ingale *et al.*, 2022)

²⁷ From (NREL, 2018)

Total H ₂ production over lifetime	6.3E+06	kg
Anhydrous ethanol (as feedstock)	1.6E+02	MJ/kg H ₂
Anhydrous ethanol (as fuel)	2.6E+01	MJ/kg H ₂
Hydrogen production rate	5.0E+03	kg H ₂ /h

Table A26 – Steam reforming ethanol system description²⁸

Inputs	Value	Unit	Observation
Electricity	4.9E-01	kWh	From Brazilian Electricity Grid
Anhydrous ethanol as feedstock	1.6E+02	MJ	From Sugarcane/Maize Ethanol
Anhydrous ethanol as fuel	2.6E+01	MJ	From Sugarcane/Maize Ethanol
Tap water	1.6E+01	kg	Tap water {BR} tap water production, conventional treatment. For steam production.
Electricity for compression	1.2E+00	kWh	From Brazilian Grid
Ethanol transportation	5.7E-01	tkm	Transport, freight, lorry 16–32 metric ton, EURO4 {RoW} transport, freight, lorry 16–32 metric ton. Average distance of 100 km
Outputs	Value	Unit	Observation
H ₂	1.0E+00	kg	Output pressure 200 bar
Emissions air	Value	Unit	Observation
CO ₂	1.3E+01	Kg	–
CH ₄	0.0E+00	kg	–

- LCI Electrolysis System

Table A27 – Electrolysis system description²⁹

Parameter	Value	Unit
Capacity	6.0E+00	MW
Hydrogen production rate	1.2E+02	kg H ₂ /h
Efficiency	6.6E+01	%
Hydrogen purity	9.9E+01	%
System lifetime	2.0E+01	years
Stack lifetime	1.0E+01	Year

²⁸ It was assumed the same system operational as SMR described in Table A20

²⁹ From (Koj *et al.*, 2017)

Stacks per AEL system	4.0E+00	Units
Annual operation	8.3E+03	h/year
Operation pressure	3.3E+01	bar
Operating temperature	8.5E+01	°C
Hydrogen output temperature	4.0E+01	°C
Electricity consumption	5.0E+01	kWh/kg H ₂
Annual electricity consumption ³⁰	5.1E+04	MWh/year
Total H ₂ production over lifetime	1.9E+07	kg H ₂

Table A28 – LCI for electrolyzer manufacturing

Outputs	Value	Unit	Process
Electrolyser	1.0E+00	Unit	–
Inputs	Value	Unit	Process
Copper	2.00E+00	t	Copper {GLO} market for copper
Steel, non–alloyed	2.00E+02	t	Steel, unalloyed {GLO} market for steel, unalloyed
Cells			
Nickel	1.90E+01	t	Steel, unalloyed {GLO} market for steel, unalloyed
Aluminum	4.50E+02	kg	Aluminium, primary, ingot {GLO} market for
Calendared rigid plastic	7.80E+02	kg	Calendering, rigid sheets {RER} production
Polytetrafluoroethylene	7.80E+01	kg	Tetrafluoroethylene {GLO} market for tetrafluoroethylene
Acrylonitrile butadiene styrene	1.60E+02	kg	Acrylonitrile–butadiene–styrene copolymer {GLO} market for acrylonitrile–butadiene–styrene copolymer
Polyphenylene sulfide	3.40E+02	kg	Polyphenylene sulfide {GLO} polyphenylene sulfide production
Polysulfones	2.60E+02	kg	Polysulfone {GLO} market for polysulfone
N–Methyl–2–pyrrolidone	1.30E+00	t	N–methyl–2–pyrrolidone {RER} N–methyl–2–pyrrolidone production
Aniline	4.90E+01	kg	Aniline {RER} aniline production
Acetic anhydride	5.40E+01	kg	Acetic anhydride {RER} market for
Terephthalic acid	8.80E+01	kg	Purified terephthalic acid {GLO} market for purified terephthalic acid
Nitric acid	3.30E+01	kg	Nitric acid, without water, in 50 solution state {RER} nitric acid production, product in 50 solution state
Hydrochloric acid	1.30E+02	kg	Hydrochloric acid, without water, in 30 solution state {RoW} market for hydrochloric acid, without water, in 30 solution state
Graphite	4.30E+02	kg	Graphite {RER} graphite production

³⁰ It was considered stack depreciation. Assumed an increasing of 5% of electricity demand for maintaining high levels of electrolyzer capacity factor (>75%) (Roeder *et al.*, 2024)

Lubricating oil	4.80E-01	kg	Lubricating oil {GLO} market for
Zirconium oxide	1.10E+00	t	Zirconium oxide {GLO} market for zirconium oxide
Carbon monoxide	1.50E+02	kg	Carbon monoxide {RoW} carbon monoxide production
Decarbonized water	1.10E+01	t	Water, decarbonised {RoW} water production, decarbonised
Deionized water	8.60E+01	t	Water, deionized {RoW} water production, deionised Cut-off, U
Electricity	3.60E+01	GJ	Electricity, medium voltage {RoW} market for electricity, medium voltage
Heat	8.80E+01	GJ	Heat, district or industrial, natural gas {RoW} market for heat, district or industrial, natural gas
Steam	7.00E+02	MJ	Heat, from steam, in chemical industry {RoW} market for heat, from steam, in chemical industry
Industrial machine production	1.60E-01	kg	Industrial machine, heavy, unspecified {GLO} market for industrial machine, heavy, unspecified
Plaster mixing	7.80E+02	kg	Plaster mixing {GLO} market for plaster mixing

Table A29 – LCI for electrolysis operation stage³¹

Inputs	Value	Unit	Process
Electricity	5.0E+01	kWh	Electricity [Photovoltaic/Wind/Brazilian mix]
Deionized water	1.1E+01	kg	Water ³² , deionized {RoW} water production, deionized
Potassium hydroxide	1.9E+00	kg	Steam, in chemical industry {GLO} market for steam, in chemical industry
Electricity for compression	9.7E-01	kWh	Electricity [Photovoltaic/Wind/Brazilian grid]
Outputs	Value	Unit	Process
H ₂	1.0E+00	Unit	At 200 bar

- LCI Photovoltaic System

Table A30 – PV system description³³

Parameter	Parameters	Unit	Reference
Location	Brazil	–	
Technology	Mono Single – Si	–	
Type of mounting	Ground-mounted	–	
Solar irradiation	1.80E+03	kWh/m ² /year	(Assunção; Schutze,

³¹ From (Koj *et al.*, 2017)

³² System electricity consumption adapted for each electrolysis scenario – wind; photovoltaic and Brazilian Grid.

³³ Based on (Frischknecht, 2020)

			2017)
Efficiency	18%	%	(Assunção; Schutze, 2017)
Area per module	1.6E+00	m ²	
Performance ratio	7.8E+01	%	(Frischknecht <i>et al.</i> , 2020)
Inverter power	2.0E+01	kW	
Lifetime	3.0E+01	years	
Total area	2.8E+05	m ²	
Weigh of each panel	2.0E+01	kg	
Nominal Power	2.3E+02	Wp	
Total power capacity (<i>on-grid system</i>)	3.7E+01	MWp	
Total power capacity (<i>off-grid system</i>)	1.1E+02	MWp	
Electricity production over lifetime (<i>on-grid system</i>)	1.5E+06	MWh	
Electricity production over lifetime (<i>off-grid system</i>)	4.6E+06	MWh	
Yield decrease	1%	%/year	(Müller <i>et al.</i> , 2021)
Numbers of inverters (<i>on-grid system</i>)	1.9E+03	units	
Numbers of inverters (<i>off-grid system</i>)	5.5E-03	units	
Weigh of each inverter 20 kW	4.6E+01	kg	(Tschümperlin <i>et al.</i> , 2016)

Table A31 – Market share for Polysilicon production

Region	China		Asia and Pacific		Americas		Europe	
Power/market share	MW	%	MW	%	MW	%	MW	%
China	6.6E+04	6.1E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00E+00	0.00E+00
Asia and Pacific	1.8E+04	1.6E+01	4.7E+03	1.0E+02	0.0E+00	0.0E+00	0.00E+00	0.00E+00
Americas	1.0E+04	9.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E+02	0.00E+00	0.00E+00
Europe	1.5E+04	1.4E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.03E+02	1.00E+02
Total	1.09E+05	100	4.67E+03	100	0.00E+00	100	5.03E+02	100

Table A32 – Market share of wafers used in cell production

Region	China		Asia and Pacific		Americas		Europe	
Power/market share	MW	%	MW	%	MW	%	MW	%
China	7.05E+04	100	2.76E+04	87	3.02E+02	100	1.15E+02	20
Asia and Pacific	0.00E+00	0	4.23E+03	13	0.00E+00	0	0.00E+00	0
Americas	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0

Europe	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.55E+02	80
Total	7.05E+04	100	3.18E+04	100	3.02E+02	100	5.70E+02	100

Table A33 – Market share of cell produced

Region	China		Asia and Pacific		Americas		Europe	
Power/market share	MW	%	MW	%	MW	%	MW	%
China	7.20E+04	98	0.00E+00	0	0.00E+00	0	0.00E+00	0
Asia and Pacific	1.20E+03	2	2.47E+03	100	3.98E+03	93	3.04E+03	84
Americas	0.00E+00	0	0.00E+00	0	3.08E+02	7	0.00E+00	0
Europe	0.00E+00	0	0.00E+00	0	0.00E+00	0	5.82E+02	16
Total	7.32E+04	100	2.47E+03	100	4.28E+03	100	3.62E+03	100

Table A34 – Market share of panels installed

Region	China		Asia and Pacific		Americas		Europe	
Power/market share	MW	%	MW	%	MW	%	MW	%
China	4.55E+04	100	3.35E+03	13	1.21E+04	75	9.10E+03	72
Asia and Pacific	0.00E+00	0	2.32E+04	87	0.00E+00	0	0.00E+00	0
Americas	0.00E+00	0	0.00E+00	0	4.10E+03	25	0.00E+00	0
Europe	0.00E+00	0	0.00E+00	0	0.00E+00	0	3.47E+03	28
Total	4.55E+04	100	2.66E+04	100	1.62E+04	100	1.26E+04	100

Table A35 – LCI for metallurgical grade (MG – silicon)

Output	NO	CN	US	APAC	Unit	Process
MG–silicon, at plant	1.00E+00	–	–	–	kg	–
MG–silicon, at plant	–	1.00E+00	–	–	kg	–
MG–silicon, at plant	–	–	1.00E+00	–	kg	–
MG–silicon, at plant	–	–	–	1.00E+00	kg	–
Emissions to air	Value	Value	Value	Value	Unit	Process
Carbon monoxide, fossil	1.38E–03	1.38E–03	1.38E–03	1.38E–03	kg	–
Carbon dioxide, biogenic	1.61E+00	1.61E+00	1.61E+00	1.61E+00	kg	–
Carbon dioxide,	3.58E+00	3.58E+00	3.58E+00	3.58E+00	kg	–

fossil						
Inputs	Value	Value	Value	Value	Unit	Process
Electricity, medium voltage, at grid, NO	1.1E+01	–	–	–	kWh	Electricity, medium voltage {NO} market for electricity, medium voltage
Electricity, medium voltage, at grid – CN	–	1.1E+01	–	–	kWh	Electricity, medium voltage {CN} market for
Electricity, medium voltage, at grid – US	–	–	1.1E+01	–	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity, medium voltage, at grid – KR	–	–	–	1.1E+01	kWh	Electricity, medium voltage {KR} market for electricity, medium voltage
Recovery wood chips, production	3.3E–03	3.3E–03	3.3E–03	3.3E–03	kg	Wood chips, dry, measured as dry mass {Europe without Switzerland} glued laminated timber production, average glue mix
Hard coal coke, at plant	2.3E+01	2.3E+01	2.3E+01	2.3E+01	MJ	Heat, district or industrial, other than natural gas {RoW} heat production, at coal coke industrial furnace 1–10MW
Graphite	1.0E–01	1.0E–01	1.0E–01	1.0E–01	kg	Graphite {RER} graphite production
Charcoal	1.7E–01	1.7E–01	1.7E–01	1.7E–01	kg	Charcoal {GLO} charcoal production
Petroleum coke, at refinery	5.0E–01	5.0E–01	5.0E–01	5.0E–01	kg	Petroleum coke {GLO} market for petroleum coke
Silica sand	2.7E+00	2.7E+00	2.7E+00	2.7E+00	kg	Silica sand {DE} silica sand production
Silicon, at plant	1.0E–11	1.0E–11	1.0E–11	1.0E–11	unit	Silicone factory {RER} silicone factory construction
Oxygen liquid	2.0E–02	2.0E–02	2.0E–02	2.0E–02	kg	Oxygen, liquid {RER} air separation, cryogenic

Table A36 – LCI for solar grade silicon production

Outputs	RER	CN	US	APAC	Unit	Process
Silicon, solar grade, modified Siemens process, at plant	1.00E+00	–	–	–	kg	
Silicon, solar grade, modified Siemens process, at plant	–	1.00E+00		–	kg	

Silicon, solar grade, modified Siemens process, at plant	–	–	1.00E+00	–	kg	
Silicon, solar grade, modified Siemens process, at plant	–	–		1.00E+00	kg	
Emission air, high population density	Value	Value	Value	Value	Unit	Process
Heat, waste	1.76E+02	1.76E+02	1.76E+02	1.76E+02	MJ	
Inputs	Value	Value	Value	Value	Unit	Process
MG–silicon, at plant	1.1E+00	–	–	–	kg	From Table A35
MG–silicon, at plant	–	1.1E+00	–	–	kg	From Table A35
MG–silicon, at plant	–	–	1.1E+00	–	kg	From Table A35
MG–silicon, at plant	–	–	–	1.1E+00	kg	From Table A35
Hydrochloric acid, 30 in H ₂ O	1.6E+00	1.6E+00	1.6E+00	1.6E+00	kg	Hydrochloric acid, without water, in 30 solution state {RER} market for hydrochloric acid, without water, in 30 solution state
Hydrogen, liquid	5.0E–02	5.0E–02	5.0E–02	5.0E–02	kg	Hydrogen, liquid {RER} market for hydrogen, liquid
Sodium hydroxide, 50 in H ₂ O, production mix	3.5E–01	3.5E–01	3.5E–01	3.5E–01	kg	Sodium hydroxide, without water, in 50 solution state {GLO} market for sodium hydroxide, without water, in 50 solution state
Transport, freight, lorry, fleet average	2.8E+00	2.8E+00	2.8E+00	2.8E+00	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified
Transport, freight, rail	3.7E+00	3.7E+00	3.7E+00	3.7E+00	tkm	Transport, freight train {Europe without Switzerland} market for transport, freight train
Electricity, at cogen 1MW lean burn, allocation exergy	1.8E+01	0.0E+00	0.0E+00	0.0E+00	MJ	Electricity, high voltage {Europe without Switzerland} heat and power co–generation, natural gas, 1MW electrical, lean burn
Electricity, hydropower, at run–of–river power plant	3.9E+00	0.0E+00	1.2E+01	0.0E+00	kWh	Electricity, high voltage {RoW} electricity production, hydro, run–of–river
Electricity medium	2.2E+01	0.0E+00	0.0E+00	0.0E+00	kWh	Electricity, medium

voltage, at grid						voltage {CN} market for
Electricity medium voltage, at grid	5.4E+00	0.0E+00	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {NO} market for electricity, medium voltage
Electricity medium voltage, at grid	0.0E+00	4.9E+01	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {CN} market for
Electricity medium voltage, at grid	0.0E+00	0.0E+00	3.7E+01	0.0E+00	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity medium voltage, at grid	0.0E+00	0.0E+00	0.0E+00	4.9E+01	kWh	Electricity, medium voltage {KP} market for electricity, medium voltage
Heat, at cogen 1MW lean burn, allocation exergy	2.9E+01	2.9E+01	2.9E+01	2.9E+01	MJ	Heat, district or industrial, natural gas {Europe without Switzerland} heat and power co-generation, natural gas, 1MW electrical, lean burn
Silicon plant	1.0E-11	1.0E-11	1.0E-11	1.0E-11	unit	Silicone factory {RER} silicone factory construction

Table A37 – Market share of silicon production globally

Outputs	CN	APAC	US	RER	Unit	Process
Silicon, production mix, photovoltaics	1.00E+00	–	–	–	kg	
Silicon, production mix, photovoltaics	–	1.00E+00		–	kg	
Silicon, production mix, photovoltaics	–	–	1.00E+00	–	kg	
Silicon, production mix, photovoltaics	–	–		1.00E+00	kg	
Inputs	Value	Value	Value	Value	Unit	Process
Silicon, solar grade, modified Siemens process	6.10E-01	0.00E+00	0.00E+00	0.00E+00	kg	From Table A36
Silicon, solar grade, modified Siemens process	1.62E-01	1.00E+00	0.00E+00	0.00E+00	kg	From Table A36
Silicon, solar grade, modified Siemens process	9.28E-02	0.00E+00	1.00E+00	0.00E+00	kg	From Table A36

Silicon, solar grade, modified Siemens process	1.35E-01	0.00E+00	0.00E+00	1.00E+00	kg	<i>From</i> Table A36
Transport	Value	Value	Value	Value	Unit	Process
Transport, transoceanic freight ship	5.37E+00	0.00E+00	0.00E+00	0.00E+00	tkm	Transport, freight, sea, transoceanic ship {GLO} transport, freight, sea, transoceanic ship
Transport, freight, rail	2.00E-01	2.00E-01	2.00E-01	2.00E-01	tkm	Transport, freight train {Europe without Switzerland} market for transport, freight train
Transport, freight, lorry, fleet average	5.00E-02	5.00E-02	5.00E-02	5.00E-02	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified

Table A38 – LCI for single-crystalline silicon production

Outputs	CN	US	APAC	RER	Unit	Process
CZ Single crystalline silicon, photovoltaics	1.00E+00	–	–	–	kg	
CZ Single crystalline silicon, photovoltaics	–	1.00E+00	–	–	kg	
CZ Single crystalline silicon, photovoltaics	–	–	1.00E+00	–	kg	
CZ Single crystalline silicon, photovoltaics	–	–	–	1.00E+00	kg	
Inputs	Value	Value	Value	Value	unit	Process
Silicon, production mix, photovoltaics	1.0E+00	–	–	–	kg	From Table A37
Silicon, production mix, photovoltaics	–	1.0E+00	–	–	kg	From Table A37
Silicon, production mix, photovoltaics	–	–	1.0E+00	–	kg	From Table A37
Silicon, production mix, photovoltaics	–	–	–	1.0E+00	kg	From Table A37
Argon, liquid, at plant	1.0E+00	1.0E+00	1.0E+00	1.0E+00	kg	Argon, liquid {RER} argon production, liquid
Hydrogen fluoride, at plant	1.0E-02	1.0E-02	1.0E-02	1.0E-02	kg	Hydrogen fluoride {RER} hydrogen fluoride production
Nitric acid, 50% in H ₂ O, at plant	6.7E-02	6.7E-02	6.7E-02	6.7E-02	kg	Nitric acid, without water, in 50 solution state {RoW} nitric acid production, product in 50 solution state

Sodium hydroxide, 50% in H ₂ O, production mix	4.2E-02	4.2E-02	4.2E-02	4.2E-02	kg	Sodium hydroxide, without water, in 50 solution state {GLO} market for sodium hydroxide, without water, in 50 solution state
Ceramic tiles, at regional storage	1.7E-01	1.7E-01	1.7E-01	1.7E-01	kg	Ceramic tile {CH} ceramic tile production
Lime, hydrated, packed	2.2E-02	2.2E-02	2.2E-02	2.2E-02	kg	Lime, hydrated, packed {CH} lime production, hydrated, packed
Electricity, medium voltage, at grid	3.2E+01	0.0E+00	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {CN} market for
Electricity, medium voltage, at grid	0.0E+00	3.2E+01	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity, medium voltage, at grid	0.0E+00	0.0E+00	3.2E+01	0.0E+00	kWh	Electricity, medium voltage {KR} market for electricity, medium voltage
Electricity, medium voltage, production ENTSO, at grid	0.0E+00	0.0E+00	0.0E+00	3.2E+01	kWh	Electricity, high voltage {ENTSO-E} production mix
Natural gas, burned in industrial furnace low NO _x > 100kW	6.8E+01	6.8E+01	6.8E+01	6.8E+01	MJ	Heat, district or industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace low – NO _x >100kw
Water, deionized	4.0E+00	0.0E+00	0.0E+00	0.0E+00	kg	Water, deionized {CH} water production, deionized
Water, deionized	0.0E+00	4.0E+00	0.0E+00	0.0E+00	kg	Water, deionized {RoW} water production, deionized
Water, deionized	0.0E+00	0.0E+00	4.0E+00	0.0E+00	kg	Water, deionized {RoW} water production, deionized
Water, deionized	0.0E+00	0.0E+00	0.0E+00	4.0E+00	kg	Water, deionized {Europe without Switzerland} water production, deionized
Water cooling, unspecified natural origin	5.1E+00	–	–	–	m ³	Water, cooling, unspecified natural origin, CN
Water cooling, unspecified natural origin	–	5.1E+00	–	–	m ³	Water, cooling, unspecified natural origin, US

Water cooling, unspecified natural origin	–	–	5.1E+00	–	m ³	Water, cooling, unspecified natural origin, IAI Area, Asia, without China and GCC
Water cooling, unspecified natural origin	–	–	–	5.1E+00	m ³	Water, cooling, unspecified natural origin, RER
Transport	Value	Value	Value	Value	Unit	Process
Transport, freight, lorry, fleet average	1.1E+00	1.1E+00	1.1E+00	1.1E+00	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified
Transport, freight, rail	1.4E+00	1.4E+00	1.4E+00	1.4E+00	tkm	Transport, freight train {Europe without Switzerland} market for transport, freight train
Silicone plant	1.0E–11	1.0E–11	1.0E–11	1.0E–11	unit	Silicone factory {RER} silicone factory construction

Table A39 – LCI for single silicon wafer production

Outputs	CN	US	APAC	RER	Unit	Process
Single– Si wafer, photovoltaics	1.00E+00	–	–	–	m ²	
Single– Si wafer, photovoltaics	–	1.00E+00		–	m ²	
Single– Si wafer, photovoltaics	–	–	1.00E+00	–	m ²	
Single– Si wafer, photovoltaics	–	–		1.00E+00	m ²	
Inputs	Value	Value	Value	Value	Unit	Process
CZ single crystalline silicon, photovoltaic	6.0E–01	–	–	–	kg	<i>From</i> Table A38
CZ single crystalline silicon, photovoltaic	–	6.0E–01	–	–	kg	<i>From</i> Table A38
CZ single crystalline silicon, photovoltaic	–	–	6.0E–01	–	kg	<i>From</i> Table A38
CZ single crystalline silicon, photovoltaic	–	–	–	6.0E–01	kg	<i>From</i> Table A38
Flat glass, uncoated	1.0E–02	1.0E–02	1.0E–02	1.0E–02	kg	Flat glass, uncoated {RER} flat glass production, uncoated
Sodium hydroxide, 50	1.5E–02	1.5E–02	1.5E–02	1.5E–02	kg	Sodium hydroxide,

in H ₂ O, production mix						without water, in 50 solution state {GLO} market for sodium hydroxide, without water, in 50 solution state
Hydrochloric acid, 30 in H ₂ O	2.7E-03	2.7E-03	2.7E-03	2.7E-03	kg	Hydrochloric acid, without water, in 30 solution state {RER} market for hydrochloric acid, without water, in 30 solution state
Acetic acid, 98 in H ₂ O	3.9E-02	3.9E-02	3.9E-02	3.9E-02	kg	Acetic acid, without water, in 98 solution state {RER} acetic acid production, product in 98 solution state
Dipropylene glycol monomethyl ether	3.0E-01	3.0E-01	3.0E-01	3.0E-01	kg	Dipropylene glycol monomethyl ether {RER} dipropylene glycol monomethyl ether production
Alkylbenzene sulfonate, linear, petrochemical	2.4E-01	2.4E-01	2.4E-01	2.4E-01	kg	Alkylbenzene sulfonate, linear, petrochemical {RER} alkylbenzene sulfonate production, linear, petrochemical
Acrylic binder, 34 in H ₂ O	2.0E-03	2.0E-03	2.0E-03	2.0E-03	kg	Acrylic binder, without water, in 34 solution state {GLO} market for
Brass	7.4E-03	7.4E-03	7.4E-03	7.4E-03	kg	Brass {RoW} brass production
Chromium steel 18/8	1.5E-03	1.5E-03	1.5E-03	1.5E-03	kg	Steel, chromium steel 18/8, hot rolled {RER} steel production, chromium steel 18/8, hot rolled
Wire drawing	9.0E-03	9.0E-03	9.0E-03	9.0E-03	kg	Wire drawing, steel {RER} wire drawing, steel
Electricity, medium voltage	4.8E+00	0.0E+00	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {CN} market for
Electricity, medium voltage	0.0E+00	4.8E+00	0.0E+00	0.0E+00	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity, medium voltage	0.0E+00	0.0E+00	4.8E+00	0.0E+00	kWh	Electricity, medium voltage {KR} market for electricity, medium voltage
Electricity, medium voltage	0.0E+00	0.0E+00	0.0E+00	4.8E+00	kWh	Electricity, high voltage {ENTSO-E} production mix
Natural gas, burned in	4.0E+00	4.0E+00	4.0E+00	4.0E+00	MJ	Heat, district or

industrial furnace low- NO _x > 100kw						industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace low- NO _x > 100kw
Water, deionised	5.6E+01	–	–	–	kg	Water, deionised {CH} water production, deionised
Water, deionised	–	5.6E+01	–	–	kg	Water, deionised {RoW} water production, deionised
Water, deionised	–	–	5.6E+01	–	kg	Water, deionised {RoW} water production, deionised
Water, deionised	–	–	–	5.6E+01	kg	Water, deionised {Europe without Switzerland} water production, deionised

Table A40 – Market share of silicon wafer production globally

Outputs	RER	US	CN	APAC	Unit	Process
Single – Si wafer, photovoltaic, at regional storage	1.00E+0 0	–	–	–	m ²	
Single – Si wafer, photovoltaic, at regional storage	–	1.00E+0 0		–	m ²	
Single – Si wafer, photovoltaic, at regional storage	–	–	1.00E+0 0	–	m ²	
Single – Si wafer, photovoltaic, at regional storage	–	–		1.00E+0 0	m ²	
Inputs	Value	Value	Value	Value	Unit	Process
Single – Si wafer	8.0E–01	–	–	–	m ²	From Table A39
Single – Si wafer	2.0E–01	1.0E+00	1.0E+00	8.7E–01	m ²	From Table A39
Single – Si wafer	–	–	–	–	m ²	From Table A39
Single – Si wafer	–	–	–	1.3E–01	m ²	From Table A39
Transport	Value	Value	Value	Value	Unit	Process
Transport, transoceanic freight ship	1.6E+00	8.2E+00	0.0E+00	1.6E+00	tkm	Transport, freight, sea, transoceanic ship {GLO} transport, freight, sea, transoceanic ship
Transport, freight, rail	8.4E–02	7.9E–02	0.0E+00	7.9E–02	tkm	Transport, freight train {Europe without Switzerland} market for

						transport, freight train
Transport, freight, lorry, fleet average	2.1E-02	2.1E-02	0.0E+00	2.0E-02	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified

Table A41 – LCI for PV cell production

Outputs	CN	US	APAC	RER	Unit	Process
Photovoltaic cell, single-Si	1.00E+00	–	–	–	m ²	
Photovoltaic cell, single-Si	–	1.00E+00	–	–	m ²	
Photovoltaic cell, single-Si	–	–	1.00E+00	–	m ²	
Photovoltaic cell, single-Si	–	–	–	1.00E+00	m ²	
Emission to air	Value	Value	Value	Value	Unit	Process
Carbon dioxide, fossil	1.67E-01	1.67E-01	1.67E-01	1.67E-01	kg	
Inputs	CN	US	APAC	RER	Unit	Process
Single-Si wafer, photovoltaics	1.0E+00	–	–	–	m ²	From Table A40
Single-Si wafer, photovoltaics	–	1.0E+00	–	–	m ²	From Table A40
Single-Si wafer, photovoltaics	–	–	1.0E+00	–	m ²	From Table A40
Single-Si wafer, photovoltaics	–	–	–	1.0E+00	m ²	From Table A40
Metallization paste, front side	3.4E-03	3.4E-03	3.4E-03	3.4E-03	kg	Metallization paste, front side {RER} metallization paste production, front side
Metallization paste, back side	1.1E-03	1.1E-03	1.1E-03	1.1E-03	kg	Metallization paste, back side {RER} metallization paste production, back side
Metallization, back side, aluminum	5.5E-02	5.5E-02	5.5E-02	5.5E-02	kg	Metallization paste, back side, aluminum {RER} metallization paste production, back side, aluminum
Ammonia, liquid, at regional storehouse	2.2E-02	2.2E-02	2.2E-02	2.2E-02	kg	Ammonia, liquid {RER} ammonia production, steam reforming, liquid
Phosphoryl chloride	1.3E-02	1.3E-02	1.3E-02	1.3E-02	kg	Phosphoryl chloride {GLO} market for
Isopropanol	1.8E-01	1.8E-01	1.8E-01	1.8E-01	kg	Isopropanol {RER}

						isopropanol production
Hydrochloric acid, 30 in H ₂ O	6.3E-04	6.3E-04	6.3E-04	6.3E-04	kg	Hydrochloric acid, without water, in 30 solution state {RER} market for hydrochloric acid, without water, in 30 solution state
Hydrogen fluoride	6.5E-04	6.5E-04	6.5E-04	6.5E-04	kg	Hydrogen fluoride {GLO} production
Sodium hydroxide, 50 in H ₂ O, production mix	6.0E-01	6.0E-01	6.0E-01	6.0E-01	kg	Sodium hydroxide, without water, in 50 solution state {GLO} market for sodium hydroxide, without water, in 50 solution state
Lime, hydrated, packed	1.5E-02	1.5E-02	1.5E-02	1.5E-02	kg	Lime, hydrated, loose weight {CH} lime production, hydrated, loose weight
Refrigerant r134a	3.1E-05	3.1E-05	3.1E-05	3.1E-05	kg	Refrigerant R134a {RER} refrigerant R134a production
Nitrogen, liquid	1.2E+00	1.2E+00	1.2E+00	1.2E+00	kg	Nitrogen, liquid {RER} air separation, cryogenic
Silane	2.9E-03	2.9E-03	2.9E-03	2.9E-03	kg	Dimethyldichlorosilane {GLO} dimethyldichlorosilane production
Tap water	1.7E+02	0.0E+00	0.0E+00	0.0E+00	kg	Tap water {RoW} tap water production, conventional treatment
Tap water	0.0E+00	1.7E+02	0.0E+00	0.0E+00	kg	Tap water {RoW} tap water production, conventional treatment
Tap water	0.0E+00	0.0E+00	1.7E+02	0.0E+00	kg	Tap water {RoW} tap water production, conventional treatment
Tap water	0.0E+00	0.0E+00	0.0E+00	1.7E+02	kg	Tap water {Europe without Switzerland} tap water production, conventional treatment
Electricity medium voltage	1.8E+01	–	–	–	kWh	Electricity, medium voltage {CN} market for
Electricity medium voltage	–	1.8E+01	–	–	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity medium voltage	–	–	1.8E+01	–	kWh	Electricity, medium voltage {KR} market for electricity, medium

						voltage
Electricity medium voltage	–	–	–	1.8E+01	kWh	Electricity, high voltage {ENTSO-E} production mix
Natural gas, burned in industrial furnace low-NO _x >100kw	6.1E-02	6.1E-02	6.1E-02	6.1E-02	MJ	Heat, district or industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace low- NO _x >100kw
Photovoltaic cell factory	4.0E-07	4.0E-07	4.0E-07	4.0E-07	Unit	Photovoltaic cell factory {DE} photovoltaic cell factory construction
Transport	Value	Value	Value	Value	Unit	Process
Transport, freight, lorry	2.7E-01	2.7E-01	2.7E-01	2.7E-01	tkm	Transport, freight, lorry, unspecified {RER} market for
Transport, freight, rail	1.5E+00	1.5E+00	1.5E+00	1.5E+00	tkm	Transport, freight train {Europe without Switzerland} market for

Table A42 – Market share of PV cell production globally

Output	RER	US	CN	APAC	Unit	Process
Photovoltaic cell, single – Si, at regional storage	1.00E+00	–	–	–	m ²	
Photovoltaic cell, single – Si, at regional storage	–	1.00E+00	–	–	m ²	
Photovoltaic cell, single – Si, at regional storage	–	–	1.00E+00	–	m ²	
Photovoltaic cell, single – Si, at regional storage	–	–	–	1.00E+00	m ²	
Inputs	Value	Value	Value	Value	Unit	Process
Photovoltaic cell, single– Si, at plant	1.61E-01	–	–	–	m ²	<i>From</i> Table A41
Photovoltaic cell, single– Si, at plant	–	7.19E-02	–	–	m ²	<i>From</i> Table A41
Photovoltaic cell, single– Si, at plant	8.39E-01	9.28E-01	1.60E-02	1.00E+00	m ²	<i>From</i> Table A41
Photovoltaic cell, single– Si, at plant	–	–	9.84E-01	–	m ²	<i>From</i> Table A41
Transport	Value	Value	Value	Value	Unit	Process
Transport, transoceanic	6.27E+00	8.03E+00	–	–	tkm	Transport, freight, sea,

freight ship						transoceanic ship {GLO} transport, freight, sea, transoceanic ship
Transport, freight, rail	9.40E-02	9.40E-02	–	–	tkm	Transport, freight train {Europe without Switzerland} market for transport, freight train
Transport, freight, lorry, fleet average	2.35E-02	2.35E-02	–	–	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified

Table A43 – LCI for PV panel production

Output	CN	US	APAC	RER	Unit	Process
Photovoltaic panel, single– Si	1.00E+00	–	–	–	m ²	
Photovoltaic panel, single– Si	–	1.00E+00	–	–	m ²	
Photovoltaic panel, single– Si	–	–	1.00E+00	–	m ²	
Photovoltaic panel, single– Si	–	–	–	1.00E+00	m ²	
Emission to air	Value	Value	Value	Value	Unit	Process
Carbon dioxide, fossil	2.18E-02	2.18E-02	2.18E-02	2.18E-02	kg	
Inputs	Value	Value	Value	Value	Unit	Process
Photovoltaic cell, single – Si, at regional storage	9.4E-01	–	–	–	m ²	From Table A42
Photovoltaic cell, single – Si, at regional storage	–	9.4E-01	–	–	m ²	From Table A42
Photovoltaic cell, single – Si, at regional storage	–	–	9.4E-01	–	m ²	From Table A42
Photovoltaic cell, single – Si, at regional storage	–	–	–	9.4E-01	m ²	From Table A42
Aluminum alloy, almg3	2.1E+00	2.1E+00	2.1E+00	2.1E+00	kg	Aluminum alloy, almg3 {RER} aluminum alloy production, almg3
Cooper, at regional storage	1.0E-01	1.0E-01	1.0E-01	1.0E-01	kg	Copper {RER} copper production, primary
Wire drawing, copper	1.0E-01	1.0E-01	1.0E-01	1.0E-01	kg	Wire drawing, copper {RER} wire drawing, copper
Diode, unspecified	2.8E-03	2.8E-03	2.8E-03	2.8E-03	kg	Diode, auxiliaries and

						energy use {GLO} diode production, auxiliaries and energy use
Silicone product	1.2E-01	1.2E-01	1.2E-01	1.2E-01	kg	Silicone product {RER} silicone product production
Tin, at regional storage	1.3E-02	1.3E-02	1.3E-02	1.3E-02	kg	Tin {RER} tin production
Lead, at regional storage	7.3E-04	7.3E-04	7.3E-04	7.3E-04	kg	Lead {GLO} market for lead
Solar glass, low-iron, at regional storage	8.8E+00	8.8E+00	8.8E+00	8.8E+00	kg	Solar glass, low-iron {RER} solar glass production, low-iron
Tempering, flat glass	8.8E+00	8.8E+00	8.8E+00	8.8E+00	kg	Tempering, flat glass {RER} tempering, flat glass
Glass fibre reinforced plastic, polyamide, injection moulding	3.0E-01	3.0E-01	3.0E-01	3.0E-01	kg	Glass fibre reinforced plastic, polyamide, injection molded {RER} glass fibre reinforced plastic production, polyamide, injection molded
Polyethylene terephthalate, granulate, amorphous,	3.5E-01	3.5E-01	3.5E-01	3.5E-01	kg	Polyethylene terephthalate, granulate, amorphous {RER} polyethylene terephthalate production, granulate, amorphous
Polyethylene, HDPE, granulate	2.4E-02	2.4E-02	2.4E-02	2.4E-02	kg	Polyethylene, high density, granulate {RoW} polyethylene production, high density, granulate
Ethylvinylacetate, foil	8.8E-01	8.8E-01	8.8E-01	8.8E-01	kg	Ethylvinylacetate, foil {RER} ethylvinylacetate production, foil
Polyvinylfluoride film	1.1E-01	1.1E-01	1.1E-01	1.1E-01	kg	Polyvinylfluoride, film {US} polyvinylfluoride, film production
Tap water	5.0E-01	–	–	–	kg	Tap water {RoW} market for tap water
Tap water	–	5.0E-01	–	–	kg	Tap water { RoW } market for tap water
Tap water	–	–	5.0E-01	–	kg	Tap water { RoW } market for tap water
Tap water	–	–	–	5.0E-01	kg	Tap water {Europe without Switzerland}

						tap water production, conventional treatment
Hydrogen fluoride	6.2E-02	6.2E-02	6.2E-02	6.2E-02	kg	Hydrogen fluoride {GLO} production
1-propanol	1.6E-02	1.6E-02	1.6E-02	1.6E-02	kg	1-propanol {RER} 1- propanol production
Isopropanol	1.5E-04	1.5E-04	1.5E-04	1.5E-04	kg	Isopropanol {RER} isopropanol production
Potassium hydroxide	5.1E-02	5.1E-02	5.1E-02	5.1E-02	kg	Potassium hydroxide {RER} potassium hydroxide production
Soap	1.2E-02	1.2E-02	1.2E-02	1.2E-02	kg	Soap {RER} soap production
Corrugated board, mixed fibre, single wall	7.6E-01	7.6E-01	7.6E-01	7.6E-01	kg	Corrugated board box {RER} corrugated board box production
EUR-flat pallet	5.0E-02	5.0E-02	5.0E-02	5.0E-02	unit	EUR-flat pallet {RER} EUR-flat pallet production
Electricity medium voltage, at grid	1.4E+01	–	–	–	kWh	Electricity, medium voltage {CN} market for
Electricity medium voltage, at grid	–	1.4E+01	–	–	kWh	Electricity, medium voltage {US} market group for electricity, medium voltage
Electricity medium voltage, at grid	–	–	1.4E+01	–	kWh	Electricity, medium voltage {KR} market for electricity, medium voltage
Electricity medium voltage, at grid	–	–	–	1.4E+01	kWh	Electricity, high voltage {ENTSO-E} production mix
Diesel, burned in building machine, average	8.8E-03	8.8E-03	8.8E-03	8.8E-03	kWh	Diesel, burned in building machine {GLO} diesel, burned in building machine
Photovoltaic panel factory	4.0E-06	4.0E-06	4.0E-06	4.0E-06	unit	Photovoltaic panel factory {GLO} photovoltaic panel factory construction
Transport	Value	Value	Value	Value	Unit	Process
Transport, freight, lorry, fleet average	2.8E+00	3.0E+00	3.0E+00	3.0E+00	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified
Transport, freight, rail	1.7E+01	1.7E+01	1.7E+01	1.7E+01	tkm	Transport, freight train {Europe without

Table A44 – Market share of PV panel production globally

Outputs	RER	US	APAC	CN	Unit	Process
Photovoltaic panel, single – Si, at regional storage	1.00E+00	–		–	m ²	
Photovoltaic panel, single – Si, at regional storage	–	1.00E+00	–	–	m ²	
Photovoltaic panel, single – Si, at regional storage	–	–	1.00E+00	–	m ²	
Photovoltaic panel, single – Si, at regional storage	–	–		1.00E+00	m ²	
Inputs	Value	Value	Value	Value	Unit	Process
Photovoltaic panel, single – Si, at plant	2.76E–01	–	–	–	m ²	From Table A43
Photovoltaic panel, single – Si, at plant	–	2.53E–01	–	–	m ²	From Table A43
Photovoltaic panel, single – Si, at plant	7.24E–01	7.47E–01	1.26E–01	1.00E+00	m ²	From Table A43
Photovoltaic panel, single – Si, at plant	–	–	8.74E–01	–	m ²	From Table A43
Transport	Value	Value	Value	Value	Unit	Process
Transport to Brazil ³⁴	–	4.16E+02	–	–	tkm	Transport, freight, sea, transoceanic ship {GLO} transport, freight, sea, transoceanic ship

Table A45 – LCI for inverter 20 kW production

Output	Value	Unit	Process
Inverter, 20 kW, average, at plant	1	Unit	Based on (Tschümperlin <i>et al.</i> , 2016)

³⁴ Average distance from China. Adapted from (Pupin *et al.*, 2023)

Inputs	Value	Unit	Process
Electricity, medium voltage, production ENTSO, at grid	4.3E+01	kWh	Electricity, high voltage {ENTSO-E} production mix
Light fuel oil, burned in industrial furnace 1MW, non-modulating	9.3E-01	MJ	Heat, district or industrial, other than natural gas {CH} heat production, light fuel oil, at industrial furnace 1MW
Natural gas burned in power plant	1.5E+01	MJ	Natural gas, burned in gas turbine {DE} natural gas, burned in gas turbine
Heat, natural gas, at industrial furnace >100kW	3.8E+01	MJ	Heat, district or industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace >100kw
Aluminum, production mix, cast alloy, at plant	2.0E+01	kg	Aluminum, cast alloy {GLO} market for aluminium, cast alloy
Aluminum alloy, almg3, at plant	8.7E-01	kg	Aluminum alloy, almg3 {RER} aluminium alloy production, almg3
Copper, at regional storage	7.9E+00	kg	Copper {RER} copper production, primary
Steel, low-alloyed, at plant	3.7E+00	kg	Steel, low-alloyed {GLO} market for steel, low-alloyed
Polypropylene, granulate, at plant	3.6E+00	kg	Polypropylene, granulate {RER} polypropylene production, granulate
Polycarbonate, at plant	8.3E-01	kg	Polycarbonate {RER} polycarbonate production
Cable, connector for computer, without plugs, at plant	5.4E-01	m	Cable, connector for computer, without plugs {GLO} cable production, connector for computer, without plugs
Inductor, ring core choke type, at plant	3.6E+00	kg	Inductor, ring core choke type {GLO} inductor production, ring core choke type
Integrated circuit, IC, logic type, at plant	2.7E-01	kg	Integrated circuit, logic type {GLO} integrated circuit production, logic type
Ferrite, at plant	1.4E-01	kg	Ferrite {GLO} ferrite production
Plugs, inlet and outlet, for network cable, at plant	1.4E+01	unit	Plug, inlet and outlet, for network cable {GLO} market for plug, inlet and outlet, for network cable
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	5.4E-01	kg	Glass fibre reinforced plastic, polyamide, injection moulded {RER} glass fibre reinforced plastic production, polyamide, injection moulded
Printed wiring board, surface mount, lead-free surface, at plant	4.2E-01	m ²	Printed wiring board, for through-hole mounting, Pb free surface {GLO} market for printed wiring board, for through-hole mounting, Pb free surface
Tin, at regional storage	3.9E-02	kg	Tin {RER} tin production
Connector, clamp connection, at plant	1.0E-01	kg	Electric connector, wire clamp {GLO} electric connector production, wire clamp
Inductor, ring core choke type, at plant	5.4E-01	kg	Inductor, ring core choke type {GLO} inductor production, ring core choke type

Inductor, miniature RF chip type, MRFI, at plant	4.5E-03	kg	Inductor, miniature radio frequency chip {GLO} inductor production, miniature radio frequency chip
Integrated circuit, IC, logic type, at plant	6.4E-01	kg	Integrated circuit, logic type {GLO} integrated circuit production, logic type
Integrated circuit, IC, memory type, at plant	7.7E-03	kg	Integrated circuit, memory type {GLO} integrated circuit production, memory type
Transistor, unspecified, at plant	7.9E-02	kg	Transistor, surface-mounted {GLO} transistor production, surface-mounted
Transistor, SMD type, surface mounting, at plant	1.7E-01	kg	Transistor, surface-mounted {GLO} transistor production, surface-mounted
Diode, glass-, SMD type, surface mounting, at plant	8.3E-03	kg	Diode, glass-, for surface-mounting {GLO} diode production, glass-, for surface-mounting
Light emitting diode, LED, at plant	5.9E-05	kg	Light emitting diode {GLO} light emitting diode production
Capacitor, film, through-hole mounting, at plant	6.8E-01	kg	Capacitor, film type, for through-hole mounting {GLO} capacitor production, film type, for through-hole mounting
Capacitor, electrolyte type, > 2cm height, at plant	1.1E+00	kg	Capacitor, electrolyte type, > 2cm height {GLO} capacitor production, electrolyte type, > 2cm height
Capacitor, electrolyte type, < 2cm height, at plant	2.8E-02	kg	Capacitor, electrolyte type, < 2cm height {GLO} capacitor production, electrolyte type, < 2cm height
Capacitor, SMD type, surface-mounting, at plant	5.5E-03	kg	Capacitor, for surface-mounting {GLO} capacitor production, for surface-mounting
Resistor, wire wound, through-hole mounting, at plant	4.6E-03	kg	Resistor, wirewound, through-hole mounting {GLO} resistor production, wirewound, through-hole mounting
Resistor, SMD type, surface mounting, at plant	1.9E-02	kg	Resistor, surface-mounted {GLO} resistor production, surface-mounted
Ferrite, at plant	1.1E-04	kg	Ferrite {GLO} ferrite production
Transformer, low voltage use, at plant	1.7E-01	kg	Transformer, low voltage use {GLO} transformer production, low voltage use
Plugs, inlet and outlet, for network cable, at plant	1.2E+00	unit	Plug, inlet and outlet, for network cable {GLO} market for plug, inlet and outlet, for network cable
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	1.1E-01	kg	Glass fibre reinforced plastic, polyamide, injection moulded {RER} glass fibre reinforced plastic production, polyamide, injection moulded
Cable, ribbon cable, 20-pin, with plugs, at plant	9.9E-04	kg	Cable, ribbon cable, 20-pin, with plugs {GLO} cable production, ribbon cable, 20-pin, with plugs
Sheet rolling, steel	3.7E+00	kg	Sheet rolling, steel {RER} sheet rolling, steel

Wire drawing, copper	7.9E+00	kg	Wire drawing, copper {RER} wire drawing, copper
Section bar extrusion, aluminum	2.0E+01	kg	Section bar extrusion, aluminium {RER} section bar extrusion, aluminium
Steel product manufacturing, average metal working	7.9E-02	kg	Metal working, average for steel product manufacturing {RER} metal working, average for steel product manufacturing
Metal working factory	4.5E-08	unit	Metal working factory {RER} metal working factory construction
Corrugated board, mixed fibre, single wall, at plant	2.7E+00	kg	Corrugated board box {RER} corrugated board box production
Folding boxboard, FBB, at plant	4.8E+00	kg	Folding boxboard carton {RER} folding boxboard carton production
Packaging film, LDPE, at plant	4.7E-02	kg	Packaging film, low density polyethylene {GLO} market for packaging film, low density polyethylene
Transport, freight, lorry, fleet average	2.8E+00	tkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified
Emissions air	Value	Unit	Process
Heat, waste	1.56E+02	MJ	–
Tap water, at user	8.17E+01	kg	–

Table A46 – LCI for PV ground-mounted system

Output	Value	Unit	Process
Ground-mounted system ³⁵	1.00E+00	m ²	Based on (Wang <i>et al.</i> , 2022)
Inputs	Value	Unit	Process
Aluminum	4.0E+00	kg/m ²	Aluminum alloy, almg3 {RER} aluminum alloy production, almg3
Steel	6.4E+00	kg/m ²	Steel, low-alloyed {GLO} market for steel, low-alloyed
Corrugated board	8.6E-02	kg/m ²	Corrugated board box {RER} corrugated board box production
Polystyrene XPS	4.5E-03	kg/m ²	Polystyrene, general purpose {RER} polystyrene production, general purpose
Polyethylene	9.1E-04	kg/m ²	Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate
Lorry > 16t	2.2E-01	tkm/m ²	Transport, freight, lorry 16–32 metric ton, EURO1 {BR} transport, freight, lorry 16–32 metric ton, EURO1
Freight rail	5.1E+00	tkm/m ²	Transport, freight train {Europe without Switzerland} market for transport, freight train
Van < 3,5t	1.1E+00	tkm/m ²	Transport, freight, lorry, unspecified {BR} transport,

³⁵ Adapted from (Wang *et al.*, 2022)

freight, lorry, all sizes, EURO1 to generic market for transport, freight, lorry, unspecified

Table A47 – Transportation from China to Brazil³⁶

Output	Value	Unit	Process
PV module	1.6E+00	m ²	PV module
Inputs	Value	Unit	Process
Photovoltaic panel, single – Si, at regional storage	1.6E+00	m ²	Photovoltaic panel, single – Si, at regional storage
Ship to Brazil	3.3E+02	tkm	Ship to Brazil

- LCI Wind Energy

Table A48 – Wind system description³⁷

Parameter	Value	Unit
Power	1.4E+01	MW
Lifetime	2.0E+01	years
Average load factor	45.0	% (ABEEólica, 2023)
Electricity production over lifetime (<i>on-grid system</i>)	9.9E+02	GWh
Electricity production over lifetime (<i>off-grid system</i>)	4.1E–01	GWh
Turbine power capacity	2.5E+00	MW
Numbers of turbines (<i>on-grid system</i>)	5.5E+00	units
Numbers of turbines (<i>off-grid system</i>)	1.7E+01	units

Table A49 – LCI for wind energy production

Inputs	Value	Unit	Process
Wind turbine, misc.	5.5E–09	unit	Table A50
Rotor blades	5.5E–09	unit	Table A51
Hub, incl. Nose cone	5.5E–09	unit	Table A52
Bed frame/plate	5.5E–09	unit	Erro! Fonte de referência não encontrada.
Generator	5.5E–09	unit	Table A54

³⁶ Based on (Pupin *et al.*, 2023)

³⁷ Adapted from (Arvesen; Hertwich, 2011)

Gearbox	5.5E-09	unit	Table A55
Low-voltage transformer	5.5E-09	unit	Table A56
Nacelle	5.5E-09	unit	Table A57
Tower	5.5E-09	unit	Table A58
Foundation	5.5E-09	unit	Table A59
Electrical collection system	3.2E-12	t	Table A60
High voltage transformer	1.3E-14	unit	Table A61
Connection to grid	2.3E-11	t	Table A62
Installation	5.5E-09	unit	
Outputs	Value	Unit	
Electricity	1.0E+00	kWh	

Table A50 – LCI for wind turbine production

Outputs	Value	Unit	Process
Wind turbine	1.0E+00	unit	
Inputs	Value	Unit	Process
Electricity	1.1E+05	kWh	Electricity, high voltage {DK} market for electricity, high voltage
Heat, waste incineration	2.2E+04	kWh	Heat, for reuse in municipal waste incineration only {DK} treatment of municipal solid waste, incineration
Heat, cogeneration	2.2E+04	kWh	Steam production, as energy carrier, in chemical industry – RoW
Gas	1.3E+04	kWh	Natural gas, burned in gas turbine {RoW} natural gas, burned in gas turbine
Diesel oil	3.9E+04	kWh	Diesel, burned in diesel-electric generating set, 18.5kW {GLO} diesel, burned in diesel-electric generating set, 18.5kW
Emissions air	Value	Unit	Process
CO ₂	1.0E+04	kg	
N ₂ O	4.0E-01	kg	
CH ₄	4.3E-01	kg	

Table A51 – LCI for rotor blades production

Outputs	Value	Unit	Process
Rotor blades	1.0E+00	unit	–
Inputs	Value	Unit	Process
Glass-reinforced plastic	2.1E+01	t	Glass fiber reinforced plastic, polyamide, injection molded {GLO} market for Alloc Def, U
Steel, low alloy	7.4E+00	t	Steel, low-alloyed {GLO} market for Alloc Def, U

Cast iron	1.5E+01	t	Cast iron {GLO} market for Alloc Def, U
Glass–reinforced plastic	5.0E–01	t	Glass fiber reinforced plastic, polyamide, injection molded {GLO} market for Alloc Def, U

Table A52 – LCI for Hub and Nose production

Inputs	Value	Unit	Process
Steel, low alloy	7.4E+00	t	Steel, low–alloyed {GLO} market for Alloc Def, U
Cast iron	1.3E+01	t	Cast iron {GLO} market for Alloc Def, U
Glass–reinforced plastic	5.0E–01	t	Glass fiber reinforced plastic, polyamide, injection molded {GLO} market for Alloc Def, U

Table A53 – LCI for bed frame and plate production

Outputs	Value	Unit	Process
Bed frame and plate	1.0E+00	unit	–
Inputs	Value	Unit	Process
Steel, low alloy	5.9E+00	t	Steel, low–alloyed {GLO} market for Alloc Def, U
Cast iron	1.1E+01	t	Cast iron {GLO} market for Alloc Def, U

Table A54 – LCI for generator production

Outputs	Value	Unit	Process
Generator	1.0E+00	unit	–
Inputs	Value	Unit	Process
Silicon, metallurgical grade	3.1E–01	t	Silicon, metallurgical grade {RoW} silicon production, metallurgical grade
Steel, low alloy	6.7E+00	t	Steel, low–alloyed {GLO} market for Alloc Def, U
Copper	3.1E+00	t	Copper {GLO} market for Alloc Def, U
Wire drawing, copper	3.1E+00	t	Wire drawing, copper {RoW} wire drawing, copper

Table A55 – LCI for gearbox production

Outputs	Value	Unit	Process
Gearbox	1,0E+00	unit	–
Inputs	Value	Unit	Process
Steel, high alloy (chromium)	1,3E+01	t	Steel, chromium steel 18/8 {GLO} market for Alloc Def, U
Cast iron	1,3E+01	t	Cast iron {GLO} market for Alloc Def, U

Table A56 – LCI for low-voltage transformer

Outputs	Value	Unit	Process
Low voltage transformer	1.0E+00	unit	–
Inputs	Value	Unit	Process
Silicon, metallurgical grade	2.4E-01	t	Silicon, metallurgical grade {RoW} silicon production, metallurgical grade
Steel, low alloy	5.2E+00	t	Steel, low-alloyed {GLO} market for Alloc Def, U
Copper	2.4E+00	t	Copper {GLO} market for Alloc Def, U
Wire drawing, copper	2.4E+00	t	Wire drawing, copper {RoW} wire drawing, copper

Table A57 – LCI for nacelle production

Outputs	Value	Unit	Process
Nacelle	1,0E+00	unit	–
Inputs	Value	Unit	Process
Steel, low alloy	1,4E+00	t	Steel, low-alloyed {GLO} market for Alloc Def, U
Steel, low alloy (chromium)	8,1E+00	t	Steel, low-alloyed {GLO} market for Alloc Def, U
Glass-reinforced plastic	3,1E+00	t	Glass fiber reinforced plastic, polyamide, injection molded {GLO} market for Alloc Def, U

Table A58 – LCI for tower production

Outputs	Value	Unit	Process
Tower	1.0E+00	unit	–
Inputs	Value	Unit	Process
Steel, low alloy	1.9E+02	t	Steel, low-alloyed {GLO} market for Alloc Def, U
Sheet rolling, steel	1.9E+02	t	Steel, low-alloyed, hot rolled {GLO} market for Alloc Def, U

Table A59 – LCI for foundation construction

Outputs	Value	Unit	Process
Foundation	1,0E+00	unit	–
Inputs	Value	Unit	Process
Concrete	9,7E+02	t	Concrete block {GLO} market for Alloc Def, U
Steel, reinforced	3,0E+01	t	Steel, chromium steel 18/8 {GLO} 30 market for Alloc Def, U

Table A60 – LCI for electrical collection system (internal cables)

Outputs	Value	Unit	Process
Electrical collection system	1.0E+00	unit	–
Inputs	Value	Unit	Process
Copper	4.3E–01	t	Copper {GLO} market for Alloc Def, U
Lead	–	t	Lead {GLO} market for lead
Steel, low alloy	–	t	Steel, low–alloyed {GLO} market for Alloc Def, U
Zinc coating (galvanizing)	–	m ²	Zinc coat, coils {RoW} zinc coating, coils
Electricity	1.12E+03	kWh	Electricity mix global ³⁸
Gas	2.13E+02	kWh	Natural gas, burned in gas turbine {RoW} natural gas, burned in gas turbine
Emissions air	Value	Unit	Process
CH ₄	4.42E+00	g	
CO ₂	5.00E+04	g	
N ₂ O	8.84E–02	g	

Table A61 – LCI for high–voltage transformer

Outputs	Value	Unit	Process
High voltage transformer	1.0E+00	unit	–
Inputs	Value	Unit	Process
Steel, low alloy	6.5E+01	t	Steel, low–alloyed {GLO} market for Alloc Def, U
Copper	1.4E+01	t	Copper {GLO} market for Alloc Def, U
Aluminum	1.2E+00	t	Aluminum, primary, ingot {GLO} market for Alloc Def, U
Silicon, metallurgical grade	1.7E+00	t	Silicon, metallurgical grade {RoW} silicon production, metallurgical grade
Electricity	7.0E+04	kWh	Electricity mix global
Gas	2.9E+05	kWh	Natural gas, burned in gas turbine {RoW} natural gas, burned in gas turbine
Emissions air	Value	Unit	Process
CH ₄	6.2E+03	g	
CO ₂	7.0E+07	g	
N ₂ O	1.3E+02	g	

³⁸ It was assumed a mix of 48% China, 22,68% USA, 13,28% Korea, 12,17% Germany and 3,87% Japan

Table A62 – LCI for connection to grid

Outputs	Value	Unit	Process
Connection to grid	1.0E+00	Unit	–
Inputs	Value	Unit	Process
Copper	2.4E–01	t	Copper {GLO} market for Alloc Def, U
Lead	3.9E–01	t	Lead {GLO} market for lead
Electricity	1.1E+03	kWh	Electricity mix global ³⁹
Gas	2.1E+02	kWh	Natural gas, burned in gas turbine {RoW} natural gas, burned in gas turbine
Emissions air	Value	Unit	Process
CH ₄	4.4E+00	g	
CO ₂	5.0E+04	g	
N ₂ O	8.8E–02	g	

Table A63 – LCI for wind system installation

Outputs	Value	Unit	Process
System installation	1.0E+00	Unit	–
Inputs	Value	Unit	Process
Diesel, on-site activities	6.0E+03	kWh	Diesel combustion ⁴⁰
Foundation transport	1.0E+00	unit	
Nacelle transport	1.0E+00	unit	
Tower transport	1.0E+00	unit	
Rotor transport	1.0E+00	unit	
Emissions air	Value	Unit	Process
CH ₄	6.7E–02	kg	
CO ₂	1.6E+03	kg	
N ₂ O	6.2E–02	kg	

Table A64 – LCI for wind components transportation

Components	Weight	Unit	Ship	Road	Unit	Process
Nacelle	4.6E+01	kg	4.6E+05	6.4E+03	tkm	Transport, freight, sea, transoceanic ship {GLO} market for Alloc Def, U –
Tower	1.4E+02	kg	1.4E+06	2.0E+04	tkm	Transport, freight, lorry >32 metric ton,

³⁹ It was assumed a mix of 48% China, 22.68% USA, 13.28% Korea, 12.17% Germany and 3.87% Japan

⁴⁰ Diesel combustion. It was considered a mixture of 14% biodiesel in volume.: diesel of 10%. For biodiesel use in Brazil, it was assumed that 83%, on average, of Brazilian biodiesel derive from soybean oil and 17% from bovine fat/tallow

Rotor	3.4E+01	kg	3.4E+05	6.7E+03	tkm	EURO5 {BR} market for transport, freight, lorry >32 metric ton, EURO5
Foundation	9.7E+02	kg	–	1.3E+05	tkm	

Table A65 – Weight wind system components

Components ⁴¹		Value	Unit
Rotor	Three blades	1.9E+01	t
	Blade hub	1.4E+01	t
	Nose cone	3.1E–01	t
Foundation	Footing	7.2E+02	t
	Ferrule	1.5E+01	t
Tower	Three sections	1.4E+02	t
	Bed frame	1.1E+01	t
	Main shaft	6.1E+00	t
Nacelle	Transformer	5.0E+00	t
	Generator	6.5E+00	t
	Gear box	1.6E+01	t
	Nacelle cover	2.0E+00	t

- LCI Electricity Grid Brazil

Table A66 – LCI for Brazil electricity mix production⁴²

Output	Value	Unit	Process
Power	1.0E+00	kWh	–
Input	Value	Unit	Process
Coal	1.8E–02	kWh	Electricity, high voltage {BR} electricity production, hard coal
Diesel	3.8E–02	kWh	Electricity, diesel, at power plants. Adapted to B14
Hydropower	6.1E–01	kWh	Electricity, high voltage {BR} electricity production, hydro, reservoir, tropical region
Natural gas	6.9E–02	kWh	Electricity, high voltage {BR} electricity production, natural gas, combined cycle power plant. Adapted with Natural gas in Brazil
Nuclear	2.2E–02	kWh	Electricity, high voltage {BR} electricity production, natural gas, conventional power plant. Adapted with Natural gas in Brazil
Sugarcane bagasse	8.0E–02	kWh	Electricity, high voltage {BR} electricity production, nuclear, pressure water reactor
Wind power	1.1E–01	kWh	Electricity, high voltage {BR} electricity

⁴¹ Weight of each component based on (Fonseca; Carvalho, 2022)

⁴² From (EPE, 2023a)

			production, oil
Photovoltaic	4.8E-02	kWh	Electricity, high voltage {BR} cane sugar production with ethanol by-product. Adapted with sugarcane production
Power losses	0.75	%	(ANEEL, 2021)
Transmission	3.2E-10	km	Transmission network, long-distance {GLO} market for
Transmission	6.6E-09	km	Transmission network, electricity, high voltage {GLO} market for Def, U.

- LCI Sugarcane Ethanol

Table A67 – Sugarcane ethanol mill description

Parameter	Value	Unit
Bagasse selling	Burnt to electricity production	
Straw recovering	50	
Boiler pressure	65	bar
Boiler efficiency	87.7	
Ethanol production	92.9	l/t sugarcane
Bioelectricity production	192.0	kWh/t sugarcane
Sugar production	–	kg/t sugarcane
Bagasse (dry basis)	2.1	kg/l ethanol
Sugarcane field productivity	80 ⁴³	t/ha
Yield	93.0 ⁴⁴	l/t sugarcane

Table A68 – LCI for sugarcane crop

Output	Value	Unit	Process
Sugarcane	8,00E+01	t	–
Input	Value	Unit	Process
Urea (N)	1.0E+02	kg	Urea, as N {RoW} urea production, as N
SST (P ₂ O ₅)	1.6E+01	kg	Single superphosphate {RoW} single superphosphate production
KCl (K ₂ O)	1.1E+02	kg	Inorganic potassium fertiliser, as K ₂ O {RoW} nutrient supply from potassium chloride
Lime	4.0E+02	kg	Lime {RoW} lime production, milled, loose

⁴³ From (Capaz *et al.*, 2021)

⁴⁴ From (Bonomi *et al.*, 2016)

Gypsum	2.0E+02	kg	Gypsum, mineral {RoW} gypsum quarry operation
Diesel	1.6E+02	l	From agricultural operations and straw loading/bailing in sugarcane crop. Adapted to B14
Glyphosate	3.9E-01	kg	Glyphosate {RoW} glyphosate production
Diuron	1.0E-01	kg	Pesticide, unspecified {RoW} pesticide production, unspecified
Carbofuran	4.2E-01	kg	Pesticide, unspecified {RoW} pesticide production, unspecified
Pesticide	9.5E-01	kg	Pesticide, unspecified {RoW} pesticide production, unspecified
Inputs transportation	7.8E+02	tkm	Transport, freight, lorry 16–32 metric ton, EURO4 {RoW} transport, freight, lorry 16–32 metric ton, EURO4
Vinasse	4.0E+01	m ³	–
Vinasse aspersion	3.1E+02	MJ	Diesel, burned in diesel–electric generating set, 10MW {GLO} diesel, burned in diesel–electric generating set, 10MW
Filter cake (db ⁴⁵) and ash	1.0E+03	kg	570.1 kg filter cake (db); 456.0 kg ash
Straw on field (db)	5.3E+00	t	
Sugarcane roots (db)	7.8E+00	t	
Emission air	Value	Unit	Process
CO ₂ , fossil	1.2E+02	kg	It was assumed a content of 0.13 kg CO ₂ per kilogram of limestone which corresponds to 0.48 kg CO ₂ per kg of limestone ⁴⁶
NO _x	5.7E-01	kg	Direct emissions are 1 of the total applied nitrogen. Indirect emissions are 1 of the nitrogen volatilized as ammonia and 0.75 of the nitrogen emitted as nitrate ⁴⁷

Table A69 – LCI for sugarcane ethanol mill⁴⁸

Outputs	Value	Unit	Process
Ethanol	9.3E+01	l	Energy allocation based on LHV
Bioelectricity	1.9E+02	kWh	Energy allocation
Input	Value	Unit	Process
Sugarcane	1.0E+00	t	From Table A68
Straw bales transportation	1.9E+00	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO4 {RoW} transport, freight, lorry 7.5–16 metric ton, EURO4
Sugarcane	3.6E+01	tkm	Transport, freight, lorry >32 metric ton, EURO4 {RoW}

⁴⁵ Dry basis

⁴⁶ As reported by (Bonomi *et al.*, 2016)

⁴⁷ Based on (Nemecek; Schnetzer, 2011)

⁴⁸ Based on (Bonomi *et al.*, 2016; Capaz *et al.*, 2021)

transportation			transport, freight, lorry >32 metric ton, EURO4
Lime	6.1E-01	kg	Quicklime, milled, packed {RoW} quicklime production, milled, packed
Sulfuric acid	4.2E-01	kg	Sulfuric acid {RoW} sulfuric acid production
Phosphoric acid	1.7E+02	g	Phosphoric acid, industrial grade, without water, in 85 solution state {RoW} purification of wet-process phosphoric acid to industrial grade, product in 85 solution state
Chemicals	3.7E+00	g	Chemical, inorganic {GLO} production
Lubricant oil	1.3E+01	g	From Brazilian refinery from Table A73
LCM ⁴⁹	2.0E-01	t	Bagasse, at industrial boiler.
Emission air	Value	Unit	Process
CO ₂ , biogenic	6.7E+01	kg	Carbon dioxide, biogenic from fermentation process
CO ₂ , biogenic	3.2E+02	kg	Carbon dioxide, biogenic from cogeneration process

- LCI Corn Ethanol

Table A70 – LCI for sugarcane ethanol mill⁵⁰

Outputs	Value	Unit
Anhydrous ethanol ⁵¹	4.3E+02	l
Raw maize oil	1.3E+01	kg
Dried distillers' grains with soluble (DDGS)	3.6E+02	kg
Electricity	1.5E+02	kWh
Inputs	Value	Unit
Maize	1.0E+03	kg
Eucalyptus	4.6E+02	kg
Maize transportation	5.0E+01	tkm ⁵²

Table A71 – LCI for corn crop cultivation

Outputs	Value	Unit	Process
Maize	7.0E+03	t	t/ha ⁵³
Emissions air	Value	Unit	Process

⁴⁹ Lignocellulosic material (dry basis) burnt in cogeneration system. Composition: (85% sugarcane bagasse, 15% sugarcane straw

⁵⁰ Based on (Moreira *et al.*, 2020)

⁵¹ Allocation Observation based on low heat value of DDGS, Anhydrous Ethanol and Raw Maize Oil

⁵² Transportation 50 km one-way (Transport, freight, lorry > 32 metric ton, EURO4 {RoW}| Rec, U). Adapted to B14

⁵³ As reported by (Moreira *et al.*, 2020)

N ₂ O	2.7E+00	kg	Estimated based on (ANP, 2024)
CO ₂ , fossil	1.9E+02	kg	Estimated based on (ANP, 2024)
CO ₂ , fossil	1.3E+00	kg	From diesel burn ⁵⁴
Inputs	Value	Unit	Process
Urea, as N	1.0E+02	kg	Urea {RoW} urea production
SST (P ₂ O ₅)	5.0E+01	kg	Single superphosphate {RoW} single superphosphate production
KCl (K ₂ O)	5.0E+01	kg	Single superphosphate {RoW} single superphosphate production
Diesel	5.0E+01	l	Diesel, burned in agricultural machinery {GLO} diesel, burned in agricultural machinery
Seeds	1.3E+01	units	Maize seed, at farm {GLO} maize seed production, at farm
Electricity	7.0E+00	kWh	From Brazilian Grid – Table A66
Dolomite	2.0E+02	kg	Dolomite {RoW} dolomite production
Pesticides, unspecified	5.0E+00	kg	Pesticide, unspecified {RoW} pesticide production, unspecified

- LCI Eucalyptus Crop Cultivation

Table A72 – LCI for eucalyptus crop cultivation⁵⁵

Outputs	Value	Unit	Process
Eucalyptus	2.6E+05	kg	kg/ha ⁵⁶
Emissions air	Value	Unit	Process
CO ₂ , fossil	2.1E+01	kg	From diesel burn ⁵⁷
CH ₄ , fossil	9.3E–01	kg	From diesel burn ⁵⁸
NO	2.0E+03	kg	Direct emissions are 1% of the total applied nitrogen. Indirect emissions are 1% of the nitrogen volatilized as ammonia and 0.75 of the nitrogen emitted as nitrate ⁵⁹
CO ₂ , fossil	2.0E–01	kg	It was assumed a content of 0.13 kg CO ₂ per kilogram of limestone which corresponds to 0.48 kg CO ₂ per kg of limestone ⁶⁰
NO _x	2.1E+01	kg	It was assumed that 21% of N ₂ O emissions are emitted as NO _x ⁶¹
Eucalyptus crop	Value	Unit	Process

⁵⁴ 3,120 g CO₂/kg diesel as reported by (ANP, 2024)

⁵⁵ Based on (Moreira *et al.*, 2020)

⁵⁶ As reported by (Couto; Nicholas; Wright, 2011) and (Pereira *et al.*, 2000)

⁵⁷ 3,120 g CO₂/kg diesel as reported by (ANP, 2024)

⁵⁸ 0.13 g CH₄/kg diesel as reported by (ANP, 2024)

⁵⁹ Based on (Nemecek; Schnetzer, 2011)

⁶⁰ As reported by (Bonomi *et al.*, 2016)

⁶¹ As reported by (Bonomi *et al.*, 2016)

Urea (N)	7.0E+01	kg	Urea, as N {RoW} production Rec, U
SST (P ₂ O ₅)	2.2E+02	kg	Phosphate fertiliser, as P ₂ O ₅ {RoW} single superphosphate production Rec, U
KCl (K ₂ O)	3.4E+02	kg	Potassium chloride, as K ₂ O {RoW} potassium chloride production
Diesel	1.0E+03	l	Diesel, burned in agricultural machinery {GLO} diesel, burned in agricultural machinery
Seeds	1.9E+03	units	Eucalyptus seedling, for planting {BR} eucalyptus seedling production, in unheated greenhouse
Dolomite	4.1E+03	kg	Dolomite {RoW} dolomite production
Pesticides, unspecified.	5.5E+01	kg	Pesticide, unspecified {RoW} pesticide production, unspecified

- LCI Fossil Diesel Production

Table A73 – Fossil diesel production at refinery⁶²

Inputs	Value	Unit	Process
Crude oil	7.7E–02	kg	Petroleum and gas production, on–shore – RoW
Crude oil	9.2E–01	kg	Petroleum and gas production, off–shore – RoW
Outputs (products)	Value	Unit	Process
Fossil diesel	3.5E–01	kg	–
Gasoline	1.9E–01	kg	–
Asphalt	2.1E–02	kg	–
Kerosene	8.4E–02	kg	–
Petroleum coke	6.1E–02	kg	–
Naphtha, at refinery	4.8E–02	kg	–
Petroleum refining coproduct	3.5E–02	kg	–
LPG ⁶³	4.8E–02	kg	–
Fuel oil,	1.6E–01	kg	–
Lubricant oil	1.3E–02	kg	–

Table A74 – Fossil diesel transportation⁶⁴

Inputs	Value	Unit	Process
Fossil diesel	1.0E+00	kg	Fossil diesel production (Table 1)
Transport (lorry)	1.9E+00	tkm	Transport, freight, lorry, all sizes, EURO3 to generic market for transport – RoW

⁶² Based on (ANP, 2023)

⁶³ LPG: Liquefied petroleum gas

⁶⁴ Based on (Costa; Capaz; Bonatto, 2023)

Transport (barge)	4.0E-01	tkm	Transport, freight, inland waterways, barge – RoW
Outputs (products)	Value	Unit	Process
Fossil diesel, on site	1,0E+00	kg	–

- LCI Landfill Biogas Production

Table A75 – Biogas characteristics

Landfill characteristics	Value	Unit	Reference
Biogas production	1.7E+02	m ³ biogas/t MSW	(EPA, 2005)
Methane fraction	5.0E+01	%	
Carbon dioxide	5.0E+01	%	
Recovery efficiency of landfill biogas	7.5E+01	%	
Total biogas recovery	1.3E+02	m ³ /t MSW	EPA. Landfill Methane Outreach Program (LMOP) – Basic Information about Landfill Gas. It was assumed 75% of biogas production in landfill can be recovered. Fugitive emissions account for 25% of biogas production
Biomethane in biogas	6.4E+01	m ³ /t MSW	(Kohlheb <i>et al.</i> , 2021)
Fugitive emissions from landfill	4.3E+01	m ³ /t MSW	
Fugitive emissions from PSA	2.0E+00	%	

Table A76 – Biogas treatment – PSA⁶⁵

Outputs	Value	Unit	Reference
Biomethane	4,90E+01	m ³	96% CH ₄ v/v
Emissions air	Value	Unit	Observation
CO ₂ , biogenic	9.7E-01	kg	
Heat, waste	1.3E+00	MJ	
Hydrogen, sulfide	6.7E-06	kg	
CH ₄ , biogenic	1.9E-03	kg	Assumed 2% of methane leakage according to Sun (2015).
Inputs	Value	Unit	
Biogas	2.1E-04	kg/t RSU	
Chemical factory	5.4E-11	p/m ³	Chemical factory, organics {RER} chemical factory construction, organics Cut-off, U
Lubricant oil	1.5E-04	kg/m ³	Lubricant oil, at refinery

⁶⁵ From Ecoinvent database “Biomethane, high pressure {RoW}| biogas purification to biomethane by pressure swing adsorption | Cut-off, U” adapted to Brazilian conditions. System has an efficiency 73%.

Potassium	4.0E-06	kg/m ³	Potassium hydroxide {GLO} market for potassium hydroxide Cut-off, U
Electricity	4.0E+01	kWh/m ³	Electricity from grid Brazil ⁶⁶
Charcoal	1.8E-01	kg/m ³	Charcoal {GLO} market for charcoal Cut-off, U

- LCI Biodiesel Production

Table A77 – Diesel blend burning⁶⁷

Outputs	Value	Unit	Process
Diesel blend	1.0E+00	kg	
Emissions air	Value	Unit	Process
CO ₂ , fossil	2.7E+00	kg	It was assumed an emissions factor of 2.603 kg CO ₂ / kg diesel; 0.000139 kg CH ₄ /kg diesel; 0.000139 kg N ₂ O/kg diesel burned as reported by GHG Protocol Brazil ⁶⁸
CH ₄ , fossil	1.4E-04	kg	
N ₂ O, fossil	1.4E-05	kg	
N ₂ O, biogenic	3.2E-06	kg	It was assumed an emissions factor of 2.431 kg CO ₂ / kg diesel; 0.00032 kg CH ₄ /kg diesel; 0.000139 kg N ₂ O/kg diesel burned as reported by GHG Protocol Brazil
CO ₂ , biogenic	3.9E-01	kg	
CO ₂ , biogenic	4.8E-04	kg	
Inputs	Value	Unit	Process
Fossil diesel	8.6E-01	kg	
Biodiesel	1.4E-01	kg	

Table A78 – Biodiesel production via methyl route⁶⁹

Inputs	Value	Unit	Process
Soy oil	8.8E-01	t	Soy oil extraction
Bovine fat	1.8E-01	t	Slaughtering of bovines
Tap water	3.5E-01	t	Tap water {BR} tap water production, conventional treatment
Methanol	1.1E-01	t	Methanol {GLO} methanol production
Sodium Methylate	2.3E-02	t	Sodium methoxide {GLO} sodium methoxide production
Hydrochloric acid	1.4E-02	t	Hydrochloric acid, without water, in 30% solution state {RoW} market for hydrochloric acid, without water, in 30%

⁶⁶ From Table A66

⁶⁷ (CNPE, 2023) stated a blend of 14% biodiesel in commercial diesel in Brazil started on 2024 March
⁶⁸ (FGV, 2024)

⁶⁹ From (Garcilasso, 2014)

			solution state
Citric acid	3.4E-03	t	Citric acid {RoW} citric acid production
Sodium hydroxide	1.5E-03	t	Sodium hydroxide, without water, in 50% solution state {GLO} market for sodium hydroxide, without water, in 50 solution state
Electricity	4.6E+01	kWh	From Brazilian Grid
Wood chips and particles	1.5E-01	t	Eucalyptus production
Fossil diesel	6.6E-03	kg	From Brazilian refinery
Raw material transportation	Value	Unit	Process
Bovine fat	2.0E+02	tkm	Transport, freight, lorry >32 metric ton, EURO3 {BR} transport, freight, lorry >32 metric ton, EURO3 . Adapted to B14.
Soy oil	1.0E+03	tkm	Transport, freight, lorry >32 metric ton, EURO3 {BR} transport, freight, lorry >32 metric ton, EURO3 . Adapted to B14.
Methanol	6.5E+01	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3. Adapted to B14.
Methanol	7.1E+02	tkm	Transport, freight, sea, transoceanic ship {GLO} transport, freight, sea, transoceanic ship. Adapted to B14.
Sodium Methylate	5.8E+00	tkm	
Hydrochloric acid	3.5E+00	tkm	
Citric acid	1.4E+00	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3. Adapted to B14.
Sodium hydroxide	3.7E-01	tkm	
Wood chips and particles	7.4E+00	tkm	
Diesel	5.0E-04	tkm	
Outputs (emissions to air)	Value	Value	Process
CO ₂ , biogenic	1.0E+02	kg	–
CO, biogenic	8.0E+01	g	–
N ₂ O	8.0E+01	g	–
CH ₄ , biogenic	3.3E+01	g	–
Outputs (products)	Value	Value	Process
Biodiesel	1.0E+00	t	–
Output (co-products)	Value	Value	Process
Glycerin (co-product)	1.3E-01	t	–
Fatty acids (co-product)	4.0E-02	t	–
Olein (co-product)	1.1E-02	t	–

Table A79 – Soybean production and harvesting⁷⁰

Output	Value	Unit	Process
Soybean	3.12E+03	kg	
Input	Value	Unit	Process
Soybean seed	4.0E+01	kg	Soybean seed, for sowing {RoW} production.
MAP, as N	7.0E+00	kg	Inorganic nitrogen fertiliser, as N {RoW} nutrient supply from monoammonium phosphate
MAP, as P ₂ O ₅	3.7E+01	kg	Inorganic phosphorus fertiliser, as P ₂ O ₅ {RoW} nutrient supply from monoammonium phosphate
SSP, as P ₂ O ₅	1.1E+01	kg	Inorganic phosphorus fertiliser, as P ₂ O ₅ {RoW} nutrient supply from single superphosphate
TSP, as P ₂ O ₅	2.2E+01	kg	Inorganic phosphorus fertiliser, as P ₂ O ₅ {RoW} nutrient supply from triple superphosphate
KCl, as K ₂ O	6.3E+01	kg	Potassium chloride, as K ₂ O {RER} potassium chloride production
Lime	5.0E+02	kg	Limestone, crushed, washed {RoW} limestone production, crushed, washed
Diesel	2.0E+01	L	From agricultural operations in soybean crop. Adapted to B14
2,4–D	1.6E–01	kg	2,4–dichlorophenol {RoW} 2,4–dichlorophenol production
Glyphosate	3.0E+00	kg	Glyphosate {RoW} glyphosate production
Pesticide	2.3E+00	kg	Pesticide, unspecified {RoW} pesticide production, unspecified
Cobalt	1.4E+00	g	Cobalt oxide {GLO} cobalt production
Input transportation	2.6E+03	tkm	Transport, freight, sea, transoceanic ship
Input transportation	4.0E–03	tkm	Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RoW}. Adapted to B14
Input transportation	1.2E+01	tkm	Transport, freight, lorry 16–32 metric ton, EURO4 {RoW}. Adapted to B14
Input transportation	6.1E+02	tkm	Transport, freight, lorry 16–32 metric ton, EURO4 {RoW}. Adapted to B14
Emission to air	Value	Unit	Process
Ammonia	3.5E–01	kg	From nitrogen fertilizer use. It was assumed 4.0% of nitrogen fertilizer is emitted as ammonia, according to (Nemecek and Kagi, 2007).
CO ₂ , fossil	1.7E+00	kg	From lime use, all carbon content in limestone is converted into carbon dioxide. 0.48 kgCarbon dioxide/kg limestone.

Table A80 – Soybean extraction⁷¹

Output	Value	Unit	Process
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⁷⁰ (Capaz *et al.*, 2021)⁷¹ Based on (Capaz *et al.*, 2021)

Soy oil	1.0E+00	kg	
Soy meal	4.9E+00	kg	
Inputs	Value	Unit	Process
Soybean	5.9E+00	kg	-
Water	4.2E+00	kg	Tap water {BR} market for tap water
Cyclohexane	7.1E+00	g	Cyclohexane {RoW} cyclohexane production
Inputs transportation	1.0E-02	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO4 {RoW} transport, freight, lorry 7.5–16 metric ton, EURO4. Adapted to B14.
Inputs transportation	1.0E-01	tkm	Transport, freight, lorry >32 metric ton, EURO4 {RoW} transport, freight, lorry >32 metric ton, EURO4. Adapted to B14.
Soybean transportation	2.3E+00	tkm	Transport, freight, lorry >32 metric ton, EURO4 {RoW} transport, freight, lorry >32 metric ton, EURO4. Adapted to B14.
Electricity	1.8E-01	kWh	Brazilian grid
Heavy oil	4.2E+00	MJ	Heavy fuel oil, burned in refinery furnace {RoW} heavy fuel oil, burned in refinery furnace

Table A81 – Bovines system production⁷²

Output	Value	Unit	Process
Cattle (carcass equivalent)	1.0E+00	kg	
Inputs	Value	Unit	Process
Area occupied by pasture	3.8E+01	m ² a	
Urea	7.1E-01	kg	Inorganic nitrogen fertiliser, as N {RoW} nutrient supply from urea
Single superphosphate	7.4E-01	kg	Single superphosphate {RoW} single superphosphate production
Limestone	2.8E+01	kg	Limestone, crushed, washed {RoW} limestone production, crushed, washed
Mineral supplement	1.0E-01	kg	Mineral supplement, for beef cattle {GLO} mineral supplement production, for beef cattle
Diesel	1.3E-01	kg	From Diesel burning
Urea	3.5E-02	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3. Adapted to B14
Single superphosphate	3.7E-02	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3. Adapted to B14
Limestone	1.4E+00	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3 . Adapted to B14
Mineral supplement	5.0E-03	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3 . Adapted to B14

⁷² From (Garcilasso, 2014)

Diesel	7.0E-03	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3 . Adapted to B14
Emissions to air	Value	Unit	Process
CH ₄ , fossil	1.5E+00	kg	Ruminant digestion
N ₂ O, fossil	1.2E-02	kg	Manure management (urine and waste). 0.012 kg N ₂ O per kg carcass produced
CO ₂ , fossil	3.2E-01	kg	Diesel burning. 0,234 kg Carbon dioxide kg per carcass produced

Table A82 – Slaughtering of bovines⁷³

Inputs	Value	Unit	Observation
Tap water	6.5E+01	kg	Tap water {BR} tap water production, conventional treatment – mix grid br
Cattle	1.1E+01	kg	
Electricity	1.1E+00	kWh	Electricity from grid Brazil
Eucalyptus chips	2.8E+00	kg	Wood chips and particles, willow {RoW} market for wood chips and particles, willow
Raw material transportation	Value	Unit	Observation
Cattle	3.9E+00	tkm	Transport, freight, lorry >32 metric ton, EURO3 {BR} transport, freight, lorry >32 metric ton, EURO3. Adapted to B14
Eucalyptus chips	1.4E-01	tkm	Transport, freight, lorry 7.5–16 metric ton, EURO3 {BR} transport, freight, lorry 7.5–16 metric ton, EURO3. Adapted to B14
Emissions to air	Value	Unit	Observation
CO ₂ , biogenic	3.1E+00	kg	From wood chips burning
CO, biogenic	4.2E-02	kg	
NO _x	4.0E-03	kg	
Particulates, < 2.5µm	2.6E-02	kg	

- Water Consumption

Table A83 – Water consumption for H₂ operation systems

Inputs	Water consumption (Liters H ₂ O/kg H ₂)			Reference
	Steam Generation	Water electrolysis	Cooling process	

⁷³ From (Garcilasso, 2014)

SREtOH	1.6E+01	–	2.4E+00	
SMR	1.3E+01	–	2.4E+00	(NELT, 2022; NREL, 2018)
SRBio	1.3E+01	–	2.4E+00	
AEL	–	1.1E+01	4.5E+00	(Lampert <i>et al.</i> , 2015)

Table A84 – Total Water Requirements for H₂ production pathways

Inputs	Resource demand (Unit/kg H ₂)	Unit	Total WC (l H ₂ O/kg H ₂)
SMR	1.3E+02	MJ	2.4E+01
SREtOH Corn	8.3E+00	Liters	1.0E+02
SREtOH Sugarcane	8.3E+00	Liters	2.2E+02
SRBiogas	1.5E+02	MJ	4.8E+01
AEL BR Grid	5.3E+01	kWh	1.5E+03
AEL BR Grid (<i>marginal</i>)	5.3E+01	kWh	2.8E+02
AEL PV (<i>ongrid</i>)	5.3E+01	kWh	3.3E+01
AEL PV (<i>offgrid</i>)	1.6E+02	kWh	1.4E+03
AEL Wind (<i>ongrid</i>)	5.3E+01	kWh	1.6E+01
AEL Wind (<i>offgrid</i>)	1.6E+02	kWh	1.4E+03

Table A85 – Water consumption by energy feedstock

Inputs	Total (l H ₂ O/unit)	Unit	Reference
Ethanol from corn	2.1E+02	Liters	(Mekonnen <i>et al.</i> , 2018; Mekonnen; Hoekstra, 2011; Mialyk <i>et al.</i> , 2022; Moreira, 2007; Pereira <i>et al.</i> , 2000)
Ethanol from sugarcane	2.7E+01	Liters	(Hernandes <i>et al.</i> , 2012; Hernandez; Bufon; Seabra, 2014; Mekonnen <i>et al.</i> , 2018; Moreira, 2007)
Biogas upgrading	9.2E–04	MJ	(Kohlheb <i>et al.</i> , 2021)
Natural Gas	4.2E–03	MJ	(Meldrum <i>et al.</i> , 2013)
Natural Gas (processing)	1.1E–03	MJ	(Meldrum <i>et al.</i> , 2013)
Natural Gas (distribution)	3.2E–03	MJ	(Meldrum <i>et al.</i> , 2013)
Electricity Grid Brazil	2.6E+01	kWh	(Ecoinvent, 2023)
Electricity from Natural Gas	4.5E+00	MWh	(Meldrum <i>et al.</i> , 2013)
Wind Electricity	4.9E–03	kWh	(Meldrum <i>et al.</i> , 2013)
Photovoltaic Electricity	3.1E–01	kWh	(Meldrum <i>et al.</i> , 2013)
Battery Lithium	4.0E+03	kg	(Mas–Fons <i>et al.</i> , 2024)

Table A86 – Water consumed locally and internationally

Inputs	$WC_{Brazil\ Operation}$ (l H ₂ O/kg H ₂)	WC_{Brazil} (l H ₂ O/kg H ₂)	WC_{Inter} (l H ₂ O/kg H ₂)
SMR	1.8E+01	6.1E+00	–
SREtOH Corn	1.8E+01	5.1E+01	3.1E+01
SREtOH Sugarcane	1.8E+01	1.7E+02	4.1E+01
SRBiogas	1.6E+01	3.2E+01	–
AEL BR Grid	1.5E+01	1.5E+03	–
AEL BR Grid (<i>marginal</i>)	1.5E+01	2.6E+02	–
AEL PV (<i>on-grid</i>)	1.5E+01	–	1.8E+01
AEL PV (<i>off-grid</i>)	1.5E+01	–	1.4E+03
AEL Wind (<i>on-grid</i>)	1.5E+01	–	2.8E–01
AEL Wind (<i>off-grid</i>)	1.5E+01	–	1.4E+03

Table A87 – AWARE Characterization Factors⁷⁴

CF_{AWARE}	Annual Default
$CF_{AWARE\ Brazil}$	26.1
$CF_{AWARE\ Global}$	42.9
$CF_{AWARE\ Paraná\ Basin}$	11.8
$CF_{AWARE\ São\ Francisco\ Basin}$	32.2
$CF_{AWARE\ Western\ Northeast\ Atlantic}$	42.9

⁷⁴ Based on (Andrade *et al.*, 2020; Boulay *et al.*, 2018)

ABBREVIATIONS

Alkaline Electrolysis	AEL
Air Separation Unit	ASU
Carbon Dioxide Equivalent	CO ₂ eq
Cumulative Energy Demand	CED
Distillers Dried Grains with Soluble	DDGS
Fossil Energy Ratio	FER
Full-time Equivalent	FTE
Global Warming Potential	GWP
Greenhouse Gases	GHG
Gross Domestic Product	GDP
Gross fixed capital formation	CAPEX
Haber Bosch Process	H-B
High Heat Value	HHV
Levelized Cost of Ammonia	LCOA
Levelized Cost of Hydrogen	LCOH
Life Cycle Assessment	LCA
Low Heat Value	LHV
Municipal Solid Waste	MSW
Operational Expenditure	OPEX
Photovoltaic	PV
Proton Membrane Exchange	PEM
Renewable Energy Source	RES
Solid Oxide Electrolyser Cell	SOEC
Steam Methane Reforming	SMR
Steam Reforming	SR
Steam Reforming of Biomethane	SRBio
Steam Reforming of Ethanol	SREthanol
Water Consumption	WC
Water Gas Shift	WGS
Water Scarcity Footprint	WSF

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PUBLICATIONS

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