



FEDERAL UNIVERSITY OF ITAJUBÁ
GRADUATE PROGRAM IN ENVIRONMENT AND
WATER RESOURCES (POSMARH)



**SPATIAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN
MINAS GERAIS AND ENVIRONMENTAL PERFORMANCE OF ITS
USE**

ANA BEATRIZ RAMOS GOULART

ITAJUBÁ - MG, 2026

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Environmental Performance of Its Use**

ANA BEATRIZ RAMOS GOULART

**Dissertation submitted to the Graduate Program in
Environmental and Water Resources (POSMARH),
for the degree of Master of Science in
Environmental and Water Resources.**

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UNIVERSIDADE FEDERAL DE ITAJUBÁ
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ATA Nº 5

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ABSTRACT

The growing demand for sustainable energy alternatives has driven global interest in green hydrogen as a strategic energy carrier in the transition toward a low-carbon economy. Brazil, due to its abundance of renewable energy resources, has significant potential for green hydrogen production. However, challenges remain regarding the identification of the most suitable regions for hydrogen production, as well as the assessment of the environmental performance associated with different supply chains. The lack of integrated information on these aspects may hinder planning and strategic decision-making processes. In this context, this study aims to identify priority regions for green hydrogen production in the state of Minas Gerais, Brazil, and to evaluate, from a Life Cycle Assessment (LCA) perspective, the environmental performance of alternative hydrogen supply chains for electricity generation in dual-fuel compression ignition engines. In the first stage, the Analytic Hierarchy Process (AHP) combined with geoprocessing techniques was used to develop thematic maps and identify the regions with the highest suitability for hydrogen production. A total of 22 parameters, ranked according to their relative importance as determined through more than 60 expert interviews, related to environmental aspects, resource availability, infrastructure, and regional development were evaluated. In the second stage, a wheel-to-well LCA was carried out considering the hydrogen supply chains originating from the regions identified as the most suitable in the AHP analysis, using a functional unit of 1 kWh of electricity generated. The analyzed supply chains comprised the direct use of compressed and liquefied hydrogen, as well as hydrogen transported and utilized in the form of green methanol and green ammonia, with production in Minas Gerais and end use in Spain. The assessment included the impact categories of global warming, fossil resource scarcity, fine particulate matter formation, ozone formation, human toxicity, and ecotoxicity. The results of the first stage identified the microregions of Uberlândia, Araxá, Pirapora, and Paracatu as the most suitable areas for green hydrogen production. The LCA results showed that renewable diesel (Hydrotreated Vegetable Oil – HVO) from waste greases currently presents the best overall environmental performance. Among the hydrogen-based alternatives, compressed hydrogen exhibited the lowest environmental impacts. However, sensitivity analysis indicates that the environmental advantage of renewable diesel is influenced by feedstock selection, and may not be maintained when non-waste feedstocks are used.

Keywords: Green Hydrogen; Analytic Hierarchy Process (AHP); Life Cycle Assessment (LCA); Priority Areas; Sustainable Production.

LIST OF FIGURES

Figure 1 - Map of Minas Gerais, Brazil	18
Figure 2 - Microregions of Minas Gerais.....	19
Figure 3 - Criteria and subcriteria	20
Figure 4 - Relative weights among the 4 adopted criteria.....	31
Figure 5 - Relative Weights among the 22 adopted subcriteria.....	32
Figure 6 - Suitability Map for H2V Production – General Scenario per Criterion (a) Resources (b) Development (c) Environmental (d) Infrastructure.....	35
Figure 7 - Suitability Map for H2V Production – Scenario 1: General.....	37
Figure 8 - Suitability Map for H2V Production – (a) Scenario 2: Wind Energy and Water Resources (b) Scenario 3: Solar Energy and Water Resources (c) Scenario 4: Biomass and Water Resources (d) Scenario 5: Water Resources.....	41
Figure 9 - Suitability Map for H2V Production of Scenario 6: Weights from Bahia.....	43
Figure 10 - Suitability (Scenario 1) and potential for green hydrogen production in Minas Gerais (Brazil), normalized values (AHP: 0.26-0.71; Potential: 0.07-3.34 MtH ₂).....	45
Figure 11 - Suitability by AHP scores and potential for green hydrogen production in Minas Gerais (Brazil).	47
Figure 12 - Life cycle assessment (LCA) scenarios evaluated in this study.	52
Figure 13 - Spatial representation of the electrolysis regions, CO ₂ sources, the Port of Santos, and the export route to Spain used in the assessed scenarios.....	53
Figure 14 - AVL 580-036 single-cylinder CI engine.....	59
Figure 15 - Global warming potential (GWP) for the evaluated scenarios.....	61
Figure 16 - Fossil resource scarcity potential for the evaluated scenarios.....	62
Figure 17 - Fine particulate matter formation potential for the evaluated scenarios.....	66
Figure 18 - Ozone formation potential for the evaluated scenarios.	68
Figure 19 - Human toxicity potential for the evaluated scenarios.....	70
Figure 20 - Environmental toxicity potential for the evaluated scenarios.....	71
Figure 21 - Sensitivity analysis of LCA results for the studied scenarios, evaluating the influence of fuel substitution rates and HVO production from fossil-based and green hydrogen sources.....	74

LIST OF TABLES

Table 1 - Levels of Importance.....	21
Table 2 - Main assumptions for biomass resource estimations	28
Table 3 - Suitability of top-10 microregions in Minas Gerais for green hydrogen production, considering different configurations on Resources-based subcriteria.	38
Table 4 - Suitability of top-10 microregions in Minas Gerais for green hydrogen production, considering different configurations on criteria.....	38
Table 5 - Territorial suitability scores and technical hydrogen production potential of the routes included in the spatially explicit life cycle assessment.....	80
Table 6 - Environmental performance of the diesel, HVO, and H ₂ -HVO scenarios across the impact categories assessed.	83

LIST OF ABBREVIATIONS AND ACRONYMS

AEL	Alkaline Electrolysis
AHP	Analytic Hierarchy Process
ASC	Ammonia Slip Catalyst
CF	Capacity Factor
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
EGR	Exhaust Gas Recirculation
ET	Environmental Toxicity
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
H ₂	Hydrogen
HT	Human Toxicity
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NH ₃	Ammonia
NO _x	Nitrogen Oxides
OF	Ozone Formation
PM	Particulate Matter
PM _{2.5}	Fine Particulate Matter
PPA	Power Purchase Agreement
PV	Photovoltaic
SAF	Sustainable Aviation Fuel
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbons
UCO	Used Cooking Oil
W	Wind

SUMMARY

1	Introduction	11
1.1.	Why Hydrogen?	11
1.2.	Why Minas Gerais?	12
1.3.	Motivation and Research Questions	13
1.4.	General Objective	14
1.5.	Specific Objectives	14
1.6.	Structure of the Dissertation	14
2	<i>Supporting Green Hydrogen Planning through Spatial Multi-Criteria and Technical Potential Analysis</i>	15
2.1.	Introduction.....	15
2.2.	Methodology	17
2.3.	Results and discussion	30
2.4.	Conclusions.....	47
	Appendix.....	48
3	<i>Spatially Explicit Life Cycle Assessment of International Green Hydrogen Supply Chains for Stationary Electricity Generation</i>	49
3.1.	Introduction.....	49
3.2.	Methodology	51
3.3.	Results and discussion	60
3.4.	Conclusions.....	77
4	General discussion and Conclusions	79
4.1.	Complementary perspectives on green hydrogen planning	79
4.2.	Trade-offs in territorial suitability assessment	80
4.3.	Trade-offs in the environmental performance of hydrogen supply chains.....	82
4.4.	Integration of both studies	85
4.5.	Future research.....	86
	Publications during Master course	87
	References	88

1 Introduction

1.1. Why Hydrogen?

The increase in global average temperatures resulting from anthropogenic CO₂ emissions and other greenhouse gases highlights the severity of the current climate crisis. Since the pre-industrial era, the planet has already warmed by approximately 1.3 °C, primarily due to the intensive use of fossil fuels (Ritchie e Roser, 2023). This scenario reinforces the urgency of developing cleaner energy alternatives.

In this context, the Paris Agreement (2015) established targets to limit global warming and achieve carbon neutrality by the middle of the 21st century (UNFCCC, 2015). Achieving these goals will require profound transformations in the global energy system. Hydrogen (H₂) has emerged as a key element in this transition, particularly in sectors where direct electrification still faces significant limitations, such as heavy transportation, steelmaking, and the chemical industry (Ali, 2022).

The growing interest in hydrogen is also driven by current global demand, which exceeds 95 million tonnes per year. However, approximately 99% of this volume is still produced from fossil fuels, generating nearly 900 million tonnes of CO₂ annually (IEA, 2023). Consequently, interest in low-carbon hydrogen has increased, particularly in green hydrogen—produced through electrolysis powered by renewable energy sources—and blue hydrogen, which is associated with carbon capture and storage technologies (IRENA, 2022a). Among these pathways, renewable-based electrolysis is considered the option most aligned with climate neutrality goals, despite its current high costs, which are expected to decrease as technologies mature and renewable electricity prices continue to decline (IEA, 2023).

The diversity of hydrogen production technologies highlights the importance of understanding their differences. Existing pathways include fossil-fuel-based routes, renewable routes such as electrolysis, photochemical and thermochemical processes, and biogenic routes that utilize biomass or biogas (Sarmah et al., 2023). Each pathway requires specific resource and infrastructure conditions. Furthermore, the hydrogen value chain involves complex logistical stages—including compression, liquefaction, and transportation—which may account for more than 30% of the final hydrogen cost (IEA, 2023). Therefore, evaluating territorial conditions is essential for identifying locations where hydrogen production is most viable.

These characteristics help explain the rapid expansion of hydrogen applications. Beyond its traditional uses in ammonia and methanol production, hydrogen is increasingly being considered for transportation, industrial heating, and green steel production (IEA, 2023). At the same time, governments and companies have significantly increased investments in the sector. More than 40 countries have launched national hydrogen strategies, and over 1,000 projects have been announced worldwide. Nevertheless, less than 1% of global hydrogen production currently qualifies as low-carbon due to high costs and regulatory uncertainties (IEA, 2023).

Within this international context, Brazil stands out because of its predominantly renewable electricity matrix, with more than 80% of electricity generation coming from clean energy sources (EPE, 2021). This characteristic creates favorable conditions for green hydrogen production in the country. To guide this development, the Brazilian National Hydrogen Program (PNH₂) established strategic guidelines aimed at

strengthening technological capabilities, supporting sector planning, and developing a qualified workforce (MME, 2021). Complementarily, the Brazilian Energy Research Office (EPE) published the report Foundations for the Consolidation of the Brazilian Hydrogen Strategy, proposing actions related to infrastructure development, regional hubs, and innovation (EPE, 2021).

1.2. Why Minas Gerais?

Green hydrogen production in Brazil can play a strategic role in both domestic and international markets. Domestically, hydrogen can contribute to the decarbonization of energy-intensive industries such as fertilizer production, cement manufacturing, and steelmaking. Internationally, the country presents significant export potential due to its abundant renewable resources and the proximity of ports with established infrastructure (IPEA, 2022).

In this context, Minas Gerais stands out not only because of its favorable natural and infrastructural conditions for solar and wind power generation but also due to its socioeconomic importance within Brazil. The state covers approximately 586,000 km², making it the fourth-largest state in the country by area, and has a population exceeding 20 million inhabitants, ranking as the second most populous state in Brazil. Economically, Minas Gerais recorded an estimated Gross Domestic Product (GDP) of BRL 1.06 trillion in 2024, corresponding to approximately 9% of the national economy (Fundação João Pinheiro, 2025).

Minas Gerais hosts one of the most diversified industrial sectors in Brazil, ranging from metallurgy and steel production to high-technology industries. In addition, the state contains significant mineral reserves—particularly iron ore, niobium, and bauxite—which support highly energy-intensive production chains. These characteristics reinforce the state's position as a potential strategic hub for green hydrogen production, utilization, and technological development, combining abundant natural resources with existing industrial demand (Governo de Minas Gerais, 2023).

However, identifying the most suitable areas for green hydrogen production in Minas Gerais requires methodologies capable of integrating multiple territorial dimensions, including renewable energy resources, water availability, infrastructure, and socio-environmental factors. Although such studies remain limited in the state, analyses conducted elsewhere in Brazil demonstrate the importance of multicriteria approaches. In Ceará, Leal, (2025) applied different multicriteria decision-making techniques combined with geographic information to classify municipalities according to their hydrogen production potential, demonstrating how variations in criteria—particularly electrical infrastructure and solar and wind resources—can substantially alter the identification of promising areas. Similarly, Rocha, (2023) used the Analytic Hierarchy Process (AHP) in Bahia to evaluate scenarios considering grid connection type, projected demand, and water availability, showing that priority areas vary according to the context analyzed. These studies indicate that site selection depends directly on the weighting of criteria and regional specificities. Therefore, the lack of similar analyses for Minas Gerais represents an important research gap and highlights the need for studies capable of integrating multiple factors to support decision-making regarding sustainable energy projects.

The Analytic Hierarchy Process (AHP), introduced by Saaty, (1990), is one of the most widely used methodologies for this type of analysis, allowing alternatives to be evaluated through pairwise comparisons of

criteria. This multicriteria method has been extensively applied in land-use planning and renewable energy site selection studies because it accommodates technical, economic, environmental, and social factors simultaneously (Saaty, 2008). Its application to green hydrogen planning has expanded rapidly in recent years, with studies conducted in countries such as Thailand (Ali, 2022), Morocco (Amrani, 2024), Pakistan (Amjad, 2024), Tunisia (Rekik, 2024), Cameroon (Flora, 2025), Portugal (Attiaoui et al., 2026), Saudi Arabia (Al-Buraiki et al., 2026), Algeria (Tiar et al., 2024), India (Thekkethil et al., 2024) and Chile (Cárdenas et al., 2026a), demonstrating its robustness as a decision-support tool for green hydrogen planning.

While AHP assists in identifying and prioritizing the most favorable locations for green hydrogen production, Life Cycle Assessment (LCA) complements this analysis by providing a detailed evaluation of environmental impacts throughout the entire hydrogen value chain. Guided by ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), LCA allows the quantification of emissions, resource consumption, and other potential environmental impacts from raw material extraction to final energy use. LCA has been extensively applied to compare hydrogen production pathways, hydrogen carriers, and end-use technologies, demonstrating that the environmental performance of hydrogen systems depends on the electricity source, conditioning processes, transportation route, and final application (Ajilouni et al., 2026; Iyer et al., 2024; Osman et al., 2024; Palmer et al., 2021; Zhang et al., 2022). Therefore, integrating AHP and LCA provides a more comprehensive framework that combines spatial, technical, and environmental dimensions, strengthening decision-making processes and supporting the development of more sustainable energy policies.

1.3. Motivation and Research Questions

Based on this approach, this study seeks to answer two complementary research questions:

- 1) **Which regions of Minas Gerais present the highest suitability for green hydrogen production?** The initial hypothesis is that suitability is determined exclusively by the availability of energy resources (wind, solar, or biomass) and is not significantly influenced by other factors such as water availability, land availability, or human resources.
- 2) **What are the environmental impacts associated with hydrogen production in the most suitable regions and its subsequent use in Europe?** The initial hypothesis is that the production stage contributes the largest share of environmental impacts.

This research is part of the Minas Gerais Hydrogen Research Network (REPHIMIGE), an initiative funded by the Minas Gerais Research Foundation (FAPEMIG) and involving five higher education institutions (UNIFEI, UFLA, UFSJ, UFJF, and PUC Minas). The main objective of the project is to evaluate the potential for green hydrogen production in Minas Gerais and assess the environmental impacts associated with its use in energy applications. To achieve this, the study applies AHP and LCA methodologies. By integrating the identification of priority production areas with the sustainability assessment of the proposed scenarios, this work aims to contribute to energy and industrial planning in Minas Gerais.

1.4. General Objective

To evaluate the territorial and environmental potential of green hydrogen in Minas Gerais through the integration of spatial multicriteria analysis and spatially explicit Life Cycle Assessment (LCA), considering its production, international transportation, and utilization in dual-fuel internal combustion engines (ICEs) for electricity generation.

1.5. Specific Objectives

- Identify the most suitable regions for green hydrogen production in Minas Gerais;
- Estimate the green hydrogen production potential of the selected regions;
- Quantify the environmental impacts associated with green hydrogen supply chains, from production to final use, through spatially explicit LCA;
- Compare the environmental performance of different hydrogen transportation pathways and utilization routes, including hydrogen-derived fuels in dual-fuel internal combustion engines for electricity generation.

1.6. Structure of the Dissertation

This dissertation is organized into four chapters:

- 1) General introduction, including context, research questions, and objectives;
- 2) *Supporting Green Hydrogen Planning Through Spatial Multi-Criteria and Technical Potential Analysis;*
- 3) *Spatially Explicit Life Cycle Assessment of International Green Hydrogen Supply Chains for Stationary Electricity Generation;*
- 4) General discussion and conclusions.

2 Supporting Green Hydrogen Planning through Spatial Multi-Criteria and Technical Potential Analysis

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Abstract

This study assesses the suitability and technical potential for green hydrogen production in Minas Gerais, Brazil, using a spatially explicit framework. By an Analytic Hierarchy Process, the suitability across 66 microregions is evaluated by applying four main criteria and 22 subcriteria that encompass environmental, resource, infrastructure, and socio-economic factors, weighted by expert judgment. In parallel, the study estimates green hydrogen production potential based on renewable electricity availability from solar, wind, biomass, and residual sources, considering electrolysis. The results indicate a total technical potential of approximately 46 Mt H₂ per year, largely dominated by solar energy (86%). Environmental restrictions emerge as the most influential factor in territorial suitability, often outweighing resource availability. Northwestern microregions show higher suitability, while some resource-rich areas remain constrained by environmental factors. Overall, regions with higher suitability align with higher production potential, highlighting the need for integrated planning approaches.

Keywords: green hydrogen; Analytic Hierarchy Process; biomass; wind power; solar power; spatially explicit analysis.

2.1. Introduction

Global energy transitions have created an urgent need to replace fossil fuels with renewable, low-carbon alternatives. Green hydrogen, which is produced from renewable sources via water electrolysis, could serve as a promising energy vector. It plays a critical role in decarbonizing sectors that are difficult to electrify, including industrial, heavy transport, and chemical industries (Ali, 2022). Its versatility, serving as a source for electricity generation, energy storage, and industrial feedstock, positions it as a key component in global strategies for climate mitigation and energy security (Yılmaz, 2025).

International interest in green hydrogen has been driven in function of its potential to substantially reduce CO₂ emissions, while also allowing surplus renewable energy generated in intermittent power systems to be used, e.g., solar and wind (Amrani, 2024). Countries like Australia, Morocco, and Tunisia have led spatial mapping and multicriteria modeling efforts to identify areas suitable for sustainable green hydrogen production (Amjad, 2024). These studies combine Multi-Criteria Decision-Making (MCDM) techniques with Geographic Information Systems (GIS), integrating technical, economic, environmental, and social factors to determine optimal locations for electrolysis plant deployment.

Of the various MCDM methods, the Analytic Hierarchy Process (AHP) has been widely applied to energy system studies, since criteria can be structurally and hierarchically weighted (Ali, 2022; Amrani, 2024; Flora, 2025; Rekik, 2024; Rocha, 2023). For example, (Amrani, 2024) applied the AHP–GIS approach to assess the territorial viability of hydrogen production from solar energy in Morocco, identifying extensive areas with high suitability based on irradiance, slope, and proximity to infrastructure. Comparable findings have been reported in Tunisia (Rekik, 2024), as well as in Thailand (Ali, 2022), Cameroon (Flora, 2025), and

Pakistan (Amjad, 2024). These studies show that integrating MCDM with GIS is a consistent and versatile method for identifying regions favorable for green hydrogen production across diverse contexts. Other recent studies with similar scope have been published in countries such as Portugal (Attiaoui et al., 2026), Saudi Arabia (Al-Buraiki et al., 2026), Algeria (Tiar et al., 2024), India (Thekkethil et al., 2024), as well as in the Brazilian state of Bahia (Governo do Estado da Bahia, 2023).

In Brazil, studies of this type remain limited, though recent research highlights Brazil's strong potential for green hydrogen production. (Leal, 2025) employed multicriteria methods to map suitability in Ceará, combining solar and wind energy data with socioeconomic and infrastructure variables. Similarly, the (Governo do Estado da Bahia, 2023) and (Rocha, 2023) used AHP in Bahia to evaluate priority scenarios for green hydrogen projects, focusing on water and energy availability. Both studies consider only the electrolysis-based route, reflecting the global trend of linking green hydrogen to renewable electricity sources. These findings underscore that Brazil's abundant renewable resources and territorial diversity call for region-specific evaluation approaches.

In parallel with these scientific advances, Brazil has strengthened its institutional and regulatory framework to foster the development of a low-carbon hydrogen economy. Notably, the National Program of Hydrogen (PNH₂) (MME, 2021) establishes strategic guidelines to promote research, innovation, and market development, while positioning the country as a competitive global supplier of clean hydrogen. Complementing this initiative, the Legal Framework for Hydrogen (Brasil, 2024) provides regulatory clarity and investment security, reinforcing national efforts toward decarbonization and sustainable industrial growth. In this context, spatially explicit and data-driven methodologies are essential to support evidence-based policymaking, guide infrastructure planning, and identify priority regions for green hydrogen production.

Minas Gerais state, Brazil, has several strategic features that allow spatial methodologies to be applied to identify areas with potential for green hydrogen production. The state is characterized by substantial climatic and topographic variability, an extensive hydrographic network, and a growing share of renewable energy in its electricity matrix, particularly photovoltaic solar. Minas Gerais holds a prominent position nationally, leading centralized solar generation in Brazil with 9 GW of installed capacity in 2024 (Secretaria de Desenvolvimento Econômico, 2024). Water availability, supported by basins such as the São Francisco and Doce rivers, enhances the potential for sustainable electrolytic processes (IDE-SISEMA, 2024). Additionally, established energy infrastructure and research institutions with strong performance in environmental and energy fields further strengthen the feasibility of state-scale green hydrogen projects.

Despite these favorable conditions, important research gaps remain. In this context, this study proposes a comprehensive and high-resolution framework for assessing the territorial suitability and production potential of green hydrogen in Minas Gerais. Beyond conventional technical, economic, and environmental criteria, the study incorporates variables rarely considered in similar assessments, including natural hazard risk areas, proximity to hospitals, and the availability of biomass and municipal solid waste, thereby offering a more holistic perspective on sustainable hydrogen deployment. Another distinctive contribution is the direct engagement of stakeholders throughout the research process. Furthermore, no prior studies have specifically examined green hydrogen potential in Minas Gerais or in inland Brazilian regions, which have historically

received less attention than coastal areas. By addressing this gap, the present research provides a robust and context-sensitive basis for strategic planning, investment decision-making, and the sustainable development of Brazil's emerging green hydrogen economy. Unlike studies conducted at the nationwide scale (Flora, 2025; Rekik, 2024; Rocha, 2023; Yılmaz, 2025), or those focusing solely on hydrogen production potential (Caravantes et al., 2024; Pous Cabello et al., 2025), our study concentrates exclusively on Minas Gerais state, taking territorial microregions as the unit of analysis. We seek to identify strategic areas for hydrogen production through two complementary approaches: (i) multicriteria suitability, and (ii) estimated production potential.

Suitability was assessed using the Analytic Hierarchy Process and Geographic Information Systems (AHP–GIS) methodology, integrating environmental, economic, resource, and infrastructure variables. Production potential was evaluated based on resource availability and established technologies. In so doing, this study highlights, for the first time, internal contrasts within the state specifically pertaining to green hydrogen viability, while also identifying potential trade-offs between the two approaches.

2.2. Methodology

The methodology was carried out in three stages: (i) describe the study area; (ii) apply the AHP–GIS methodology to assess suitability; and (iii) estimate total green hydrogen production potential in function of territory.

We should note that green hydrogen production in this study refers to water electrolysis derived green hydrogen using renewable electricity sourced from wind turbines, photovoltaic panels, or thermal systems powered by residual solid biomass or biogas.

Study Area

This study focuses exclusively on the state of Minas Gerais in southeastern Brazil, which lies between 14° and 22° south (latitude), and 39° and 51° west (longitude) (Figure 1). With an area of about 586,528 km², the state is irregularly shaped. The geography features plateaus, mountain ranges, and extensive depressions, resulting in diverse relief, climate, and socioeconomic conditions. Minas Gerais borders Bahia and Goiás to the north, Espírito Santo and Rio de Janeiro to the east and southeast, São Paulo to the south, and Mato Grosso do Sul and the Federal District to the west. Although it lacks a coastline, the state contains major hydrographic basins, such as the São Francisco, Doce, Paranaíba, and Grande rivers, that are crucial for water supply and electricity generation.

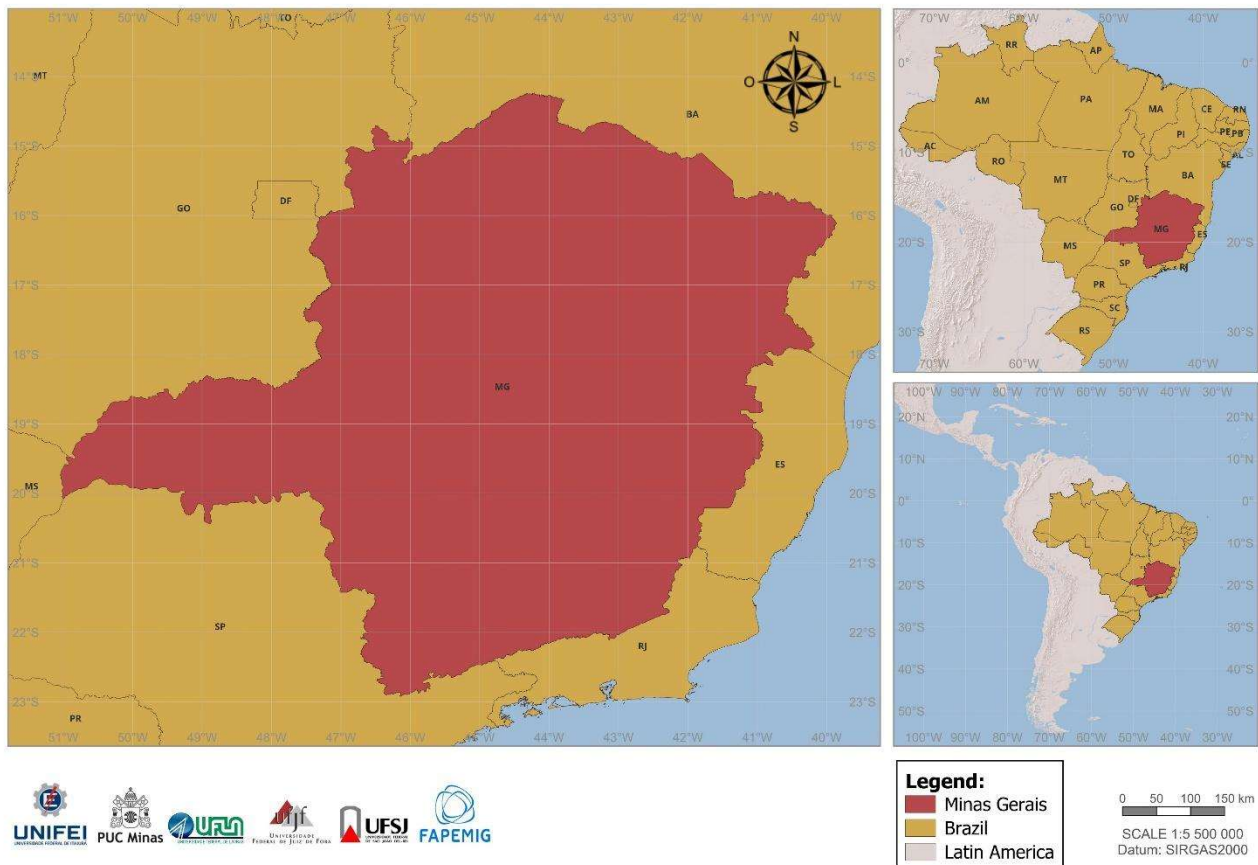


Figure 1 - Map of Minas Gerais, Brazil

From an economic and productive perspective, Minas Gerais comprises 853 municipalities and has a highly diversified economy. In 2024, the state's Gross Domestic Product (GDP) was estimated at BRL\$ 1.06 trillion, representing approximately 9% of Brazil's national economy (Fundação João Pinheiro, 2025). Key sectors include industry, agriculture, and services, with significant contributions from mining and steelmaking, as well as the metal-mechanical, automotive, chemical, and food industries.

In recent years, Minas Gerais has established itself as a national leader in photovoltaic solar energy generation, driven by favorable public incentive policies and high levels of solar irradiation. The state recently reached 13.3 GW of installed solar capacity, exceeding the total generation of more than 160 countries, split between 7.86 GW of centralized generation and 5.45 GW of distributed generation (Agência Minas., 2025). Minas Gerais alone accounts for over 36% of Brazil's total solar power generation (Agência Minas, 2024).

Beyond solar energy, the state also has substantial biomass potential. Minas Gerais is Brazil's largest coffee producer, responsible for 53% of national output, and is a significant producer of corn, accounting for 6.32% of the country's total production (FAEMG, 2023).

As part of its environmental planning strategies, Minas Gerais implemented the Water Security Plan (PMSH) to manage the state's water resources. Launched in 2022 and scheduled to conclude in 2026, the plan aims to ensure water availability for domestic supply, productive activities, and environmental preservation, while accounting for regional differences and periods of scarcity. Key actions include improving supply

infrastructure, protecting water sources, and promoting efficient water use, with particular focus on the most vulnerable regions.

The spatial analysis in this study covered the 66 microregions of Minas Gerais, following official divisions from the Brazilian Institute of Geography and Statistics (IBGE) (see Figure 2). This division reflects socioeconomic and environmental similarities, as well as interactions among municipalities.

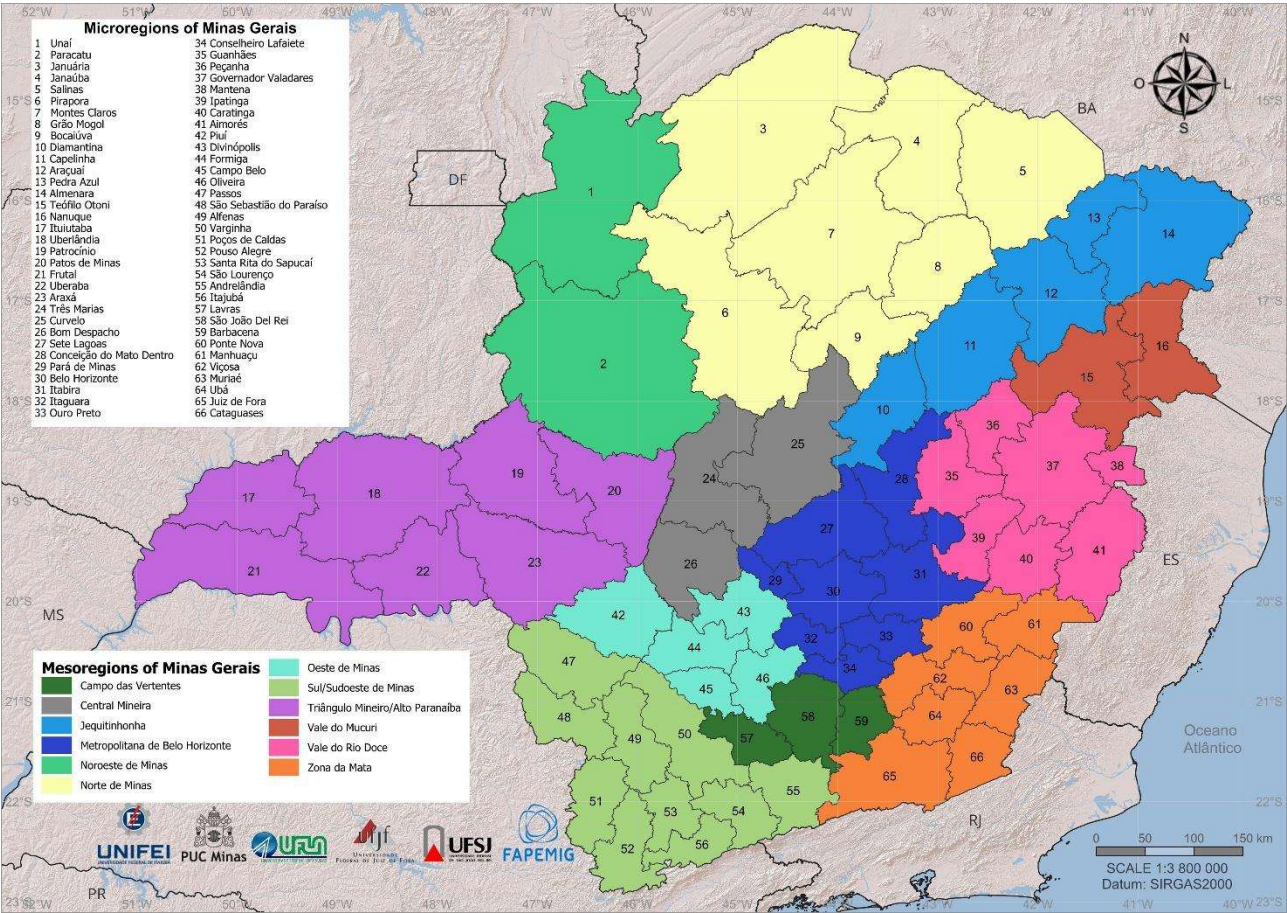


Figure 2 - Microregions of Minas Gerais

Territorial suitability assessment

The territorial suitability analysis for green hydrogen production in Minas Gerais was carried out in three phases: (i) define the relevant Minas Gerais-specific criteria and sub-criteria; (ii) prepare the thematic maps for each validated sub-criterion, spatially representing the variables of interest across the microregions; and (iii) apply the Analytic Hierarchy Process (AHP) for hydrogen production potential, with weights assigned by experts via structured questionnaires.

Defining and Validating the Criteria

The first step comprised validating the parameters used to assess territorial suitability for green hydrogen production. An online questionnaire was conducted between October 17 and November 18, 2024, collecting 50 qualified responses from representatives of universities, public agencies, energy sector companies, and associations linked to the hydrogen value chain. The initial selection of criteria was based on

the Green Hydrogen (H₂V) Atlas of Bahia [9], which provided a reference for adapting and validating the parameters most relevant to the context of Minas Gerais.

This process consolidated the four main criteria and twenty-two subcriteria (Figure 3), encompassing the essential dimensions for conducting the territorial assessment. These include socioeconomic development, environmental constraints and potential, infrastructure availability, and energy and water resources. The range of subcriteria reflects the multidimensional nature of the analysis, aligning with the principles of sustainability, safety, and technical feasibility required for the implementation of green hydrogen production facilities.

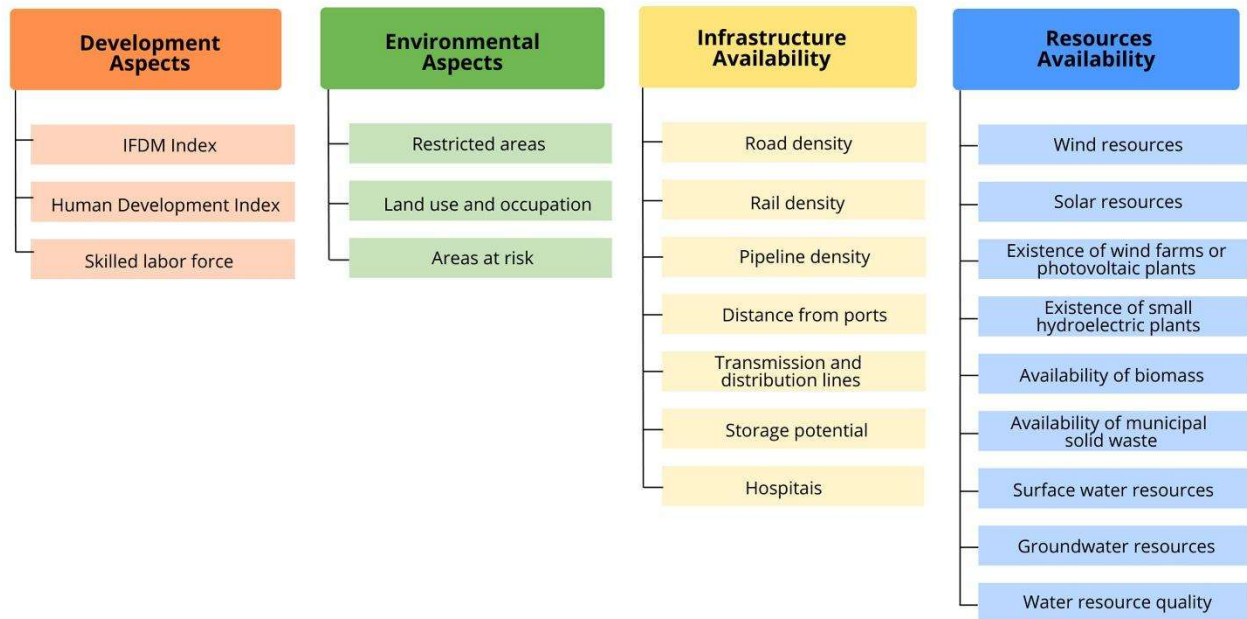


Figure 3 - Criteria and subcriteria

Preparing the Thematic Maps

The data were processed, normalized in the range from 0 to 1, and spatialized in a Geographic Information System (GIS) using the QGIS software program to prepare the maps, thereby allowing us to create thematic layers suitable for multicriteria analysis.

Information originally organized by municipalities, river basins, and aquifers was aggregated to the microregion scale to ensure compatibility across the study's various units of analysis. This procedure involved two main steps:

- (i) municipal data were aggregated to the microregion level using sums or weighted averages, depending on the variable; and
- (ii) river basin and aquifer data were converted by identifying overlaps with microregions and redistributing values proportionally to the area each hydrographic unit occupies within each microregion.

This approach ensured that each microregion accurately represents the fraction of basins it actually contains, maintaining spatial consistency, and enabling integration with other variables at the same territorial scale. Additional details are provided in the Supplementary Material section.

Weighting the Criteria and Subcriteria

Criteria and subcriteria were weighted using the Analytic Hierarchy Process (AHP) method developed by (Saaty, 1990). AHP structures decision problems hierarchically by decomposing them into different levels. In this study, the hierarchy comprised three levels:

- (i) **Main objective:** identify the microregions of Minas Gerais with the highest suitability for green hydrogen production;
- (ii) **Criteria and subcriteria:** as shown in Figure 3;
- (iii) **Alternatives:** the 66 microregions of Minas Gerais.

Relative weights were assigned based on interviews and a structured questionnaire administered to experts in energy, territorial planning, and sustainability, including representatives from government, industry, and academia. Experts were selected through purposive sampling, considering their technical expertise, institutional relevance, and direct involvement in the hydrogen value chain in the state.

The survey was conducted between March 13 and June 13, 2025, yielding twelve responses from eight entities directly involved in or affected by the hydrogen value chain in the state. The expert evaluations were organized into pairwise comparison matrices, reflecting the relative importance of each criterion. A simplified version of Saaty's AHP scale was employed to reduce cognitive complexity and facilitate expert judgments (Table 1).

Table 1 - Levels of Importance

Numerical Scale	Description
1/5	Much less important
1/3	Less important
1	Equal importance
3	More important
5	Much more important

For each specialist, five pairwise comparison matrices were constructed: four related to the main criteria — Development Aspects, Environmental Aspects, Infrastructure Availability, and Resources Availability — and a fifth matrix comparing these four criteria. The Consistency Ratio (CR) was calculated to ensure the logical consistency of the comparisons. This metric compares the Consistency Index (CI), derived from the expert judgments, with a Random Index (RI) predefined by (Saaty, 1990). Consistency is expressed by Equation 1.

$$CR = \frac{CI}{RI} \quad (1)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

Where:

- λ_{max} = the maximum eigenvalue of the comparison matrix;
- n = the number of criteria compared.

Consistency analysis was performed for each group of criteria. CR values below 0.1 were said to be acceptable, indicating coherence among judgments and reliability of the resulting weights (Saaty, 2008). Among these, the most representative matrix was selected based on the convergence of expert evaluations, with preference given to the matrix exhibiting the lowest CR.

For the matrix comparing the four main criteria, an aggregation approach based on the arithmetic mean of the weights assigned by all specialists was adopted. This procedure ensured a balanced representation of expert perspectives.

Normalized eigenvectors were calculated using the consolidated matrices to represent the relative weights of each criterion and subcriterion. This was done by normalizing the geometric means of the rows, following the methodology proposed by (Saaty, 1990). These weights indicate the percentage contribution of each factor to the overall objective and were subsequently applied to integrate thematic maps in the GIS environment.

The final weights were organized into spreadsheets and used to combine thematic layers within the GIS. Each geographic layer corresponding to a subcriterion was weighted according to its relative importance in the evaluation step, allowing us to integrate of multiple dimensions into a composite territorial suitability index. In this index, areas with more favorable conditions are assigned higher values, providing a spatial representation of suitability for green hydrogen production.

Evaluating the scenarios

The main results were expressed in Scenario 1, considering the weighting provided by stakeholders for the four criteria and 22 subcriteria. The sensitivity of these results to methodological choices was evaluated through two approaches:

- i) Considering the objectives of the present study, the weights of the subcriteria related to resource availability were varied (in four distinct scenarios) in order to analyze convergence and discrepancies with the estimated production potential. In this approach, the relative weights of the criteria were kept as in Scenario 1.
- ii) Considering different perceptions regarding the relevance of the criteria in decision-making, the weight of the four criteria analyzed (see Figure 3) was varied in eight scenarios, based on suggestions from Refs. (Hosseini Dehshiri; Hosseini Dehshiri, 2022; Pinto, 2025; Rekik, 2024; Taoufik; Fekri, 2023) In this approach, the relative weights of the subcriteria were kept as in Scenario 1.

Based on the variation in the weight of the subcriteria, the following scenarios were considered:

- Scenario 2 – Suitability with Emphasis on Wind Resources: Apply AHP with the four criteria and 17 subcriteria. Within the Resources criterion, only the following subcriteria were considered: availability of wind resources, availability of water resources, and water quality. The weights of these subcriteria were normalized relative to each other.
- Scenario 3 – Suitability with Emphasis on Solar Resources: Apply AHP with the four criteria and 18 subcriteria. Within the Resources criterion, only the following subcriteria were considered: availability of solar resources, availability of water resources, water quality, and presence of photovoltaic plants. The weights of these subcriteria were normalized relative to each other.
- Scenario 4 – Suitability with Emphasis on Biomass Resources: Apply AHP with the four criteria and 17 subcriteria. Within the Resources criterion, only the following subcriteria were considered: availability of biomass, availability of waste, availability of water resources, and water quality. The weights of these subcriteria were normalized relative to each other.
- Scenario 5 – Water Resource Availability: Apply AHP with the four criteria and 22 subcriteria. Within the Resources criterion, the availability and quality of water resources received a higher relative importance than the other subcriteria.

In turn, considering specifically the variation in the weight of the criteria, the following scenarios were considered:

- Scenario 6: This scenario used the weights for the four main criteria from the Bahia Green Hydrogen Atlas [9], which were: Resource Availability (0.383), Environmental Aspects (0.280), Infrastructure Availability (0.191), and Development Aspects (0.145). These were included to evaluate how applying a weighting structure from another state influenced results for Minas Gerais. The relative weights of the 22 subcriteria used in this study remained unchanged.
- Scenario 7: In an egalitarian approach, it was assumed that the four criteria would have the same importance in decision-making;
- Scenarios 8 - 11: In each scenario, each criterion was assigned a higher relevance compared to the others, which, in turn, were evaluated with equal weight.

The weights considered for each evaluated scenario are presented in the supplementary material.

Fitness Classification

Map keys were standardized to a range of 0.07 to 0.78 for all scenarios, corresponding to the full observed range of suitability values. This standardization ensured that all scenarios were presented on the same scale, allowing us to directly compare the results.

Continuous suitability values were aggregated at the microregion level by calculating the average AHP score for each area, after generating the final land suitability map using the AHP model. Based on these

averages, microregions were reclassified into five distinct classes according to standardized suitability ranges. This approach converted continuous values into discrete categories, facilitating spatial analysis, interpretation of territorial patterns, and comparison among microregions.

The reclassified microregion map was used to calculate spatial statistics for each level of territorial suitability to quantify the extent of each suitability class.

Territorial estimations of hydrogen production potential

Hydrogen production was estimated exclusively based on resource availability, including solar energy, wind energy, biomass, municipal solid waste, and industrial effluents. Production was said to occur via water electrolysis using PEM (Proton Exchange Membrane) technology, with a specific energy consumption of 55 MWh/tH₂ (Tenhumberg; B  ker, 2020) and an operational time of 8,322 hours per year. Resource availability was first estimated at the municipal level and then aggregated to the microregional level.

Solar resources

Photovoltaic electricity generation was estimated using Equation 3, considering an average installed power density of 40 MW/km² for solar parks.

$$E_{PV,i} = \left(10\% \cdot (A_i - A_{r,i}) \right) \cdot 40 \cdot PSH \cdot PR \cdot 365 \quad (3)$$

Where:

- $E_{PV,i}$ = potential photovoltaic energy produced in municipality i (MWh/year);
- A_i = area of municipality i (km²);
- $A_{r,i}$ = Restricted area in municipality i for installing the solar park (km²);
- PR = performance ratio (78%), according to (Fernandes et al., 2024)

The reference photovoltaic power density (40 MW/km²) was taken from the Bahia Hydrogen Production Atlas [9] . Reported land-use requirements of 5.5–8.9 acres/MWac (Bolinger; Bolinger, 2022) and 3–5 acres/MW (Ong et al., 2013) correspond to approximately 30–50 MW/km². This range was similar to the power density from the Jana  ba-MG Solar Complex, the largest solar plant in Minas Gerais, which has an installed capacity of 1.2 GWp, and occupies 30.69 km² (39.1 MW/km²).

Restricted areas were determined based on: (i) environmental constraints; and (ii) Land Use and Land Cover (LULC) restrictions.

The environmental restrictions map incorporates Conservation Units (UCs), Private Natural Heritage Reserves (RPPNs), Indigenous lands, *quilombola* communities, and slopes exceeding 20%. The Land Use and Land Cover (LULC) restrictions map includes urban areas, water bodies, active mining sites, and areas already designated for photovoltaic installations. Total restricted areas were determined by combining the environmental and LULC restriction maps, with area estimates derived from the maps generated in the

previous step. It should be noted that the area occupied by existing solar parks in each municipality was subtracted from the available area. The extent of these installed parks was calculated from the installed capacity of each generator registered with the National Electric Energy Agency (ANEEL, 2025), assuming a power density of 40 MW/km². Furthermore, it was assumed that only 10% of the remaining available area in each municipality would be used for new solar park installations.

Peak Sun Hours (PSH, hours/day), representing average daily solar irradiance (kWh/m²·day), were assigned to each municipality based on its geographical location, according to (CRESESB, 2025). The values correspond to global tilted irradiance at an inclination equal to the latitude of each location.

Wind resources

Wind speed data for Minas Gerais were obtained from the MERRA-2 database (The Second Modern-Era Retrospective Analysis for Research and Applications) to estimate wind potential. MERRA-2 is a global atmospheric reanalysis produced by NASA, providing continuous meteorological and climate data since 1980. The Land Surface Forcings collection, identified as M2I1NXLFO and developed by (Bosilovich, 2016), includes hourly wind speed measurements under the attribute “SPEEDLML.” For this study, five years were selected to construct the historical series: 2000, 2005, 2010, 2015, and 2020. Municipal coordinates correspond to the centroid of each territory, as reported by the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2024).

Municipal wind speed distributions were modeled using the Weibull distribution (Equation 4). The Weibull parameters k and c , as well as the mean wind speed, were estimated using the Maximum Likelihood Estimation (MLE) method (Aziz et al., 2023) (Equations 5–7).

$$p(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (4)$$

Where:

- k = the form-factor parameter;
- c = scale parameter;
- v = speed (m/s).

$$k = \left[\frac{\sum_{i=1}^m v_i^k \cdot \ln(v_i)}{\sum_{i=1}^m v_i^k} - \frac{\sum_{i=1}^m \ln(v_i)}{m} \right]^{-1} \quad (5)$$

$$c = \left[\frac{1}{m} \sum_{i=1}^m v_i^k \right]^{1/k} \quad (6)$$

$$V = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \quad (7)$$

Where:

- m = number of observations;
- v_i = wind speed measured at interval i ;

- V = average speed.

The municipal wind speed series, initially measured at a height of 10 m, were extrapolated to 150 m using Equation 8 (Governo do Estado da Bahia, 2023).

$$v(z) = v(z_0) \cdot \left(\frac{z}{z_0}\right)^\alpha \quad (8)$$

Where:

- $v(z)$ = wind speed at height z (m/s);
- $v(z_0)$ = velocity measured at the reference height z_0 (m/s);
- z = desired height (m);
- z_0 = reference height (m);
- $\alpha = 0.03$ (typical of an open area with few trees and buildings).

A Vestas V150 4.5 MW turbine (150 m rotor diameter, 4.5 MW nominal power) was selected for this study (Vestas, 2024). Turbines in the 4 MW class account for over 79 GW of installed capacity worldwide and cover various wind categories. This model is suitable for low-wind-speed conditions, making it particularly appropriate for onshore applications in inland regions. The turbine power curve was defined with the following parameters:

- v_{cut} (3.0 m/s);
- $v_{cut-out}$ (24.5 m/s);
- $v_{nominal}$ (12.0 m/s); and
- power coefficient = $C_p = 0.4$.

Wind power was calculated using Equation 9 and subsequently used to estimate the capacity factor for each municipality (Equation 11). Municipalities with an average wind speed below 7.0 m/s were excluded from the analysis.

$$P_w = \int P_w(v) \cdot p(v) \cdot dv \quad (9)$$

Where:

- P_w = Average total power of the wind turbine (MW);
- $P_w(v)$ = Wind turbine power, based on the characteristics given above and Equation 10;
- $p(v)$ = Probability density function of a wind regime at a given location, considering the Weibull distribution.

$$P(v) = \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \cdot C_p \quad (10)$$

Where:

- $P(U)$ = Average wind turbine power (MW);
- ρ = air density (1.225 kg/m³);

- A = area swept by the turbine blades (m^2);
- C_p = power coefficient (0.4).

$$CF = \frac{P_w}{P_n} \quad (11)$$

Where:

- P_w = Average total power of the wind turbine;
- P_n = Rated power.

The wind farm was designed with turbine spacing that results in a power density of 4.0 MW/km^2 , as recommended by the Bahia Hydrogen Atlas (Governo do Estado da Bahia, 2023). [12] More conservative and outdated estimates are reported in the Brazilian Wind Atlas (Amarante et al., 2001) (2 MW/km^2 , 2001) and in the Minas Gerais Energy Company (CEMIG) Wind Atlas (CEMIG, 2012) (1.5 MW/km^2 , 2010), both of which adopt more restrictive assumptions regarding turbine spacing, exclusion zones, and overall land-use constraints. In contrast, the selected value reflects a more optimized layout configuration, which is considered more appropriate for large-scale planning studies focused on theoretical maximum potential under favorable technical conditions. The available area was subject to the same constraint considerations described in the previous section. Total annual energy generation (8,760 hours) was then estimated using Equation 12.

$$E_{w,i} = \left(10\% \cdot (A_i - A_{r,i}) \right) \cdot 4 \cdot CF \cdot 8760 \quad (12)$$

Where:

- $E_{PV,i}$ = potential wind energy produced in municipality i (MWh/year);
- A_i = area of municipality i (km^2);
- $A_{r,i}$ = Restricted area in municipality i for installing the solar park (km^2);
- CF = capacity factor for municipality i.

Biomass and waste resources

The potential for electricity generation from biomass was estimated based on the Minas Gerais Biomass Atlas (Atlas de Biomassa de Minas Gerais, 2017), which accounts for agricultural residue, wood residue, and methane derived from Municipal Solid Waste (MSW), and animal effluents. Resources with defined destinations and established industrial uses, such as sugarcane bagasse, vinasse, and soybean straw (Lal, 2005; Seabra, 2008), were excluded from this analysis. In general, the biomass potential was calculated using the following parameters:

- Biomass Factor (BF): representing the amount of residual biomass produced;
- Collection Factor (CoF): representing the fraction of residual biomass collected;
- Net Calorific Value (NCV): representing the energy content available after accounting for moisture; and
- the efficiency of converting biomass or biogas into electricity.

Conversion plants were said to operate 8,322 hours per year. Table 2 summarizes the assumptions used in these calculations. Specific assumptions for municipal solid waste are described below.

Table 2 - Main assumptions for biomass resource estimations

Resource	Formula	Observations
Coffee straw	$E_{coffee,i}(MWh) = \frac{m_{coffee} \cdot BF \cdot NCV \cdot CoF \cdot \eta}{3.6} \quad (13)$	$m_{coffee, i}$: Annual production of coffee (t) in municipality i; BF: 1.0; NCV: 14.22 GJ/t (13.6% moisture); CoF : 0.4; η : 0.15 (20bar-boiler; atmospheric-pressure condensing turbine).
Maize residues	$E_{maize,i}(MWh) = \frac{m_{maize} \cdot BF \cdot NCV \cdot CoF \cdot \eta}{3.6} \quad (14)$	m_{maize} : Annual production of maize (t) in municipality i; BF: 2.2; NCV: 14.83 GJ/t (11.0% moisture); AF : 0.4; η : 0.15 (20bar-boiler; atmospheric-pressure condensing turbine).
Wood residues	$E_{wood,i}(MWh) = \frac{V_{wood} \cdot \rho \cdot BF \cdot NCV \cdot \eta}{3.6} \quad (15)$	V_{wood} : eucalyptus production (m ³) in municipality i; ρ : 0.5 t/m ³ ; BF: 0.5; NCV: 12.61 GJ/t (25.0% moisture); BF: 0.5; NCV: 12.61 GJ/t (25.0% moisture); η : 0.15 (20bar-boiler; atmospheric-pressure condensing turbine).
Animal effluents	$E_{AE,i}(MWh) = \frac{(365 \cdot N_{cattle,i} \cdot B \cdot P_b \cdot C_{CH_4,i} \cdot \rho^{-1}) \cdot LHV \cdot \eta}{3.6 \cdot 10^{-3}} \quad (16)$	$N_{cattle,i}$: cattle in municipality i (herd size), bovine herd, swine herd and poultry; B: daily biomass produced per capita, 10 kg (bovine herd), 2.25 kg (swine herd), 0.18 kg (poultry); P_b : biogas production (g _{biogas} /kg _{biomass}), 37 g (bovine herd), 62 g (swine herd), 55 g (poultry); $C_{CH_4,i}$: methane concentration, 60% (bovine herd), 66% (swine herd),

		60% (poultry); ρ : 0.74 (kg/m ³ , STP); LHV: 36.00 (MJ/m ³ , STC); η : 0,28.
MSW	$E_{MSW,i}(MWh) = \frac{\left(\frac{m_{CH_4}}{\rho}\right) \cdot 1000 \cdot LHV \cdot \eta}{3.6 \cdot 10^{-3}} \quad (17)$	$m_{CH_4,i}$: potential methane obtained from MSW generated in municipality I; ρ : 0.74 (kg/m ³ , STP); LHV: 36.00 (MJ/m ³ , STC); η : 0,28.

The theoretical methane production from all MSW generated in Minas Gerais in 2022 was estimated following the IPCC (IPCC, 2006) methodology (Equation 18).

$$Q_{CH_4} = \left(RSU_T \cdot RSU_F \cdot MCF \cdot COD \cdot COD_f \cdot F \cdot \frac{16}{12} - R \right) \cdot (1 - OX) \quad (18)$$

Where:

- RSU_T = Quantity of municipal solid waste generated (t/year);
- RSU_F = Fraction of MSW disposed of in landfills;
- MCF = Methane correction factor;
- COD = Degradable organic carbon (kg C/kg MSW);
- COD_f = Fraction of COD that actually degrades (%);
- F = Methane fraction in landfill biogas;
- $\frac{16}{12}$ = Conversion of carbon to methane;
- R = Methane recovery (tCH₄/year);
- OX = Methane oxidation factor;

The method assumes that all potential methane emissions occur in the same year that the waste was disposed of. A general Methane Correction Factor (MCF) of 0.6 was adopted. The fraction of degradable organic carbon (COD) varies according to the composition of the waste (Equation 19).

$$COD = (0.4 A) + (0.17 B) + (0.15 C) + (0.3 D) \quad (19)$$

Where:

- A = Fraction of waste corresponding to paper and textiles (%);
- B = Fraction of waste from gardens and parks (%);
- C = Fraction of waste corresponding to food waste (%);
- D = Fraction of waste corresponding to wood and straw (%);

The portions of each waste type were taken from the study *Gravimetric Characterization of MSW in the State of Minas Gerais* (FEAM, 2017), resulting in:

- paper and textiles (15%),
- garden and park waste (6%),
- food waste (39%),
- and wood and straw (1%).

The fraction of degradable carbon also depends on temperature, as shown in Equation 20.

$$CODf = 0.014 \cdot T + 0.28 \quad (20)$$

Where:

- T = Temperature (°C), taken as 35°C.

The methane factor (F) represents the portion of methane in the biogas generated. Landfill biogas typically contains 50–60% methane, with 0.5 taken as the standard IPCC value. Methane recovery (R) accounts for the fraction of methane captured and either used or flared. In this study, a theoretical value of R = 1 was assumed, meaning all methane is recovered. The Methane Oxidation Factor (OX) was set to 0.

2.3. Results and discussion

Weighting the criteria and subcriteria

The distribution of weights assigned to the four criteria showed that environmental aspects were the most influential factor in territorial suitability for hydrogen production, accounting for 49% of the total weight (Figure 4). Legal restrictions, protection of sensitive areas, and natural hazards strongly limit suitability, determining whether an area can support new projects. This pattern corroborates other studies, e.g., (Ali, 2022; Pinto, 2025) emphasized that safeguarding water bodies, maintaining buffer zones around protected areas, and avoiding land-use conflicts are essential for sustainable planning and risk reduction. In this context, a conservative approach was adopted regarding land availability assumptions. All protected areas were grouped into a single restriction category to avoid overestimating suitable land, and were uniformly treated as restricted despite differences in their management regimes. This ensures a more cautious estimation of territorial suitability.

The Resource Availability criterion carries an intermediate weight of 29%, highlighting that strong solar, wind, hydro, or biomass potential enhances technical feasibility. Infrastructure accounts for 15% of the total weight, reflecting its influence on cost efficiency and logistics. Finally, Development Aspects have the lowest weight (7%), serving as complementary factors in determining overall suitability.

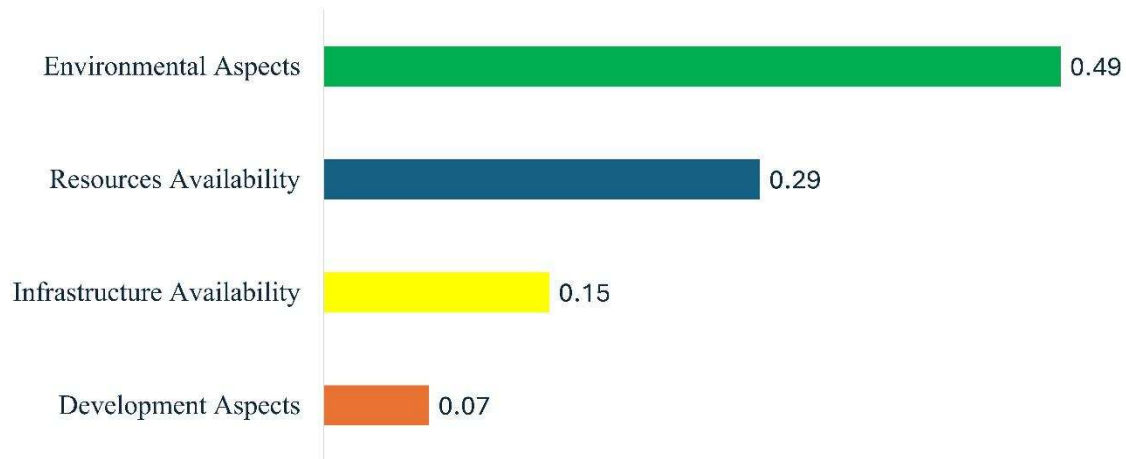


Figure 4 - Relative weights among the 4 adopted criteria

A notable difference can be observed in the criteria hierarchy when comparing these results with the weights used in the Bahia Hydrogen Atlas (Governo do Estado da Bahia, 2023), wherein Resource Availability is assigned the greatest importance, with a weight of 38.3%, followed by Environmental Aspects (28%), Infrastructure Availability (19.1%), and Development Aspects (14.5%). That study, which prioritizes areas with abundant natural resources for electricity generation, reflects an approach primarily focused on the economic feasibility of electrolytic hydrogen production, since electricity accounts for a large portion of production costs (Kotowicz; Baszczeńska; Niesporek, 2024; Santana et al., 2024). In contrast, as noted earlier, Environmental Aspects receive the highest weight in Minas Gerais, clearly reflecting expert perspectives on the factors shaping potential green hydrogen supply chains in the state.

Analyzing the weights of the 22 subcriteria showed which factors were most important in evaluating the territory of Minas Gerais. According to Figure 5, the Restricted Areas subcriterion had the highest weight (29.4%), highlighting the critical role of legal restrictions and land-use limitations in defining suitability. This is followed by Land Use and Occupation (9.8%), emphasizing the need to assess whether existing activities may constrain new developments, and Areas at Risk (9.8%), which also carries high relevance because regions prone to landslides, floods, or inundation hinder infrastructure installation and increase operational costs.

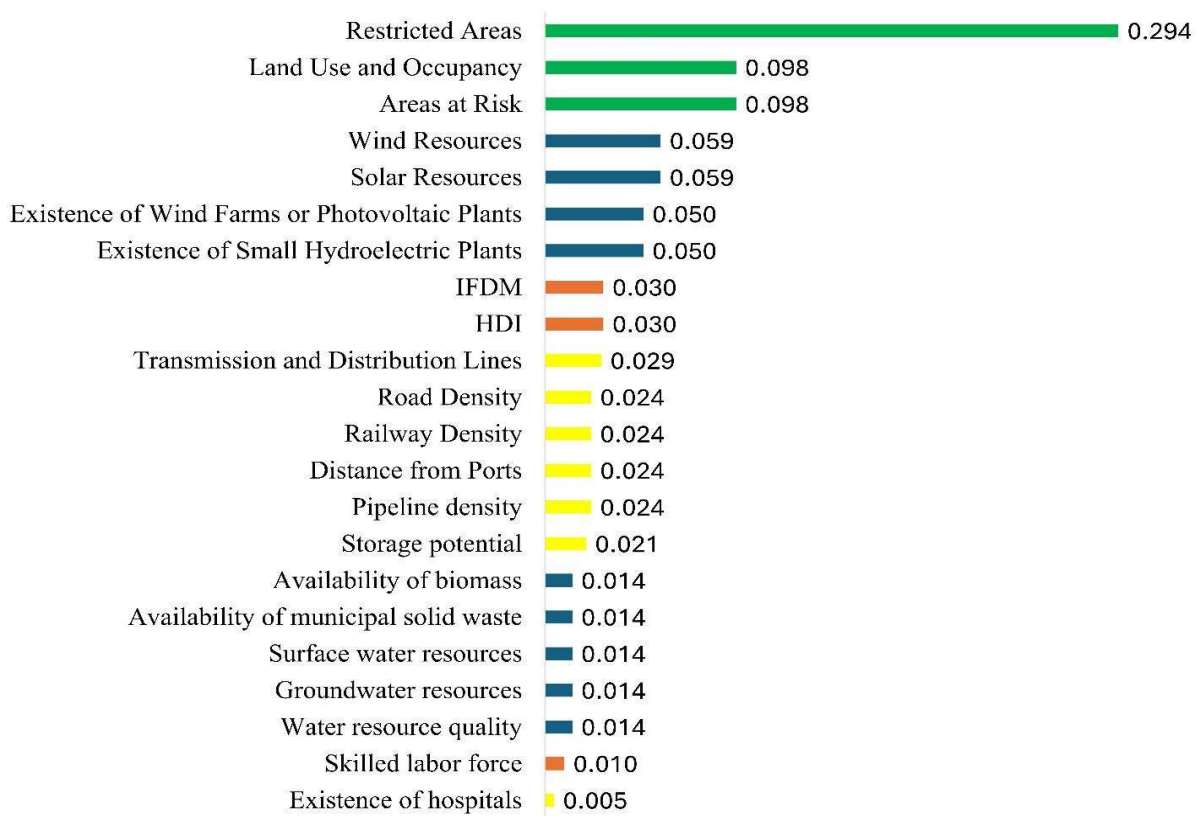


Figure 5 - Relative Weights among the 22 adopted subcriteria.

Next are the energy-related factors, with solar and wind resources each contributing 5.9%. Subcriteria associated with the distribution of existing energy infrastructure, such as the presence of wind farms, photovoltaic plants, and small hydroelectric plants (5% each), receive intermediate weights. These reflect areas where energy potential is already being harnessed, indicating both the economic viability of resource development and the presence of local infrastructure to support new electricity generation projects. Similarly, socioeconomic indicators e.g., IFDM and HDI (3% each) carry lower weights, as they describe general development conditions but do not directly determine territorial suitability.

Logistics-related criteria, including transmission lines, road density, rail density, distance from ports, pipeline density, and storage capacity (ranging from 2.1% to 2.9%), showed moderate importance. They influence the efficiency and cost of implementation but do not exclude areas from consideration.

Biomass and Municipal Solid Waste (MSW) proved to be less important, with a weight of 1.4%, compared to solar and wind resources, indicating that: (i) Respondents linked green hydrogen production via electrolysis primarily to electricity from wind or solar sources (Louli et al., 2026; Mansilha et al., 2026); (ii) Electrolysis is seen to be more technologically mature than biomass gasification (Di Nardo; De Rinaldis; Di Benedetto, 2025; Mansilha et al., 2026; Zheng et al., 2025); and (iii) Biomass and waste are seen as playing a secondary role in hydrogen production (Jiang et al., 2026; Liu et al., 2024).

Subcriteria with lower weights, e.g., surface and groundwater resources and water quality (all 1.4%), also show limited influence in the initial stage of territorial selection. While water is essential for electrolysis, expert responses indicate that its availability is unlikely to be a limiting factor in Minas Gerais, given the state's

abundance and diversity of water sources. This perception of the interviewees is consistent with the hydrological structure of Minas Gerais, where surface water availability is generally supported by extensive river basins and where groundwater resources provide an additional buffering capacity, reducing the likelihood of water scarcity acting as a first-order constraint at the territorial screening level. Moreover, water demand for hydrogen production is modest compared with other industrial uses, reducing pressure on existing resources.

However, literature suggests that this may underestimate potential constraints. Silva and Capaz (Silva; Capaz, 2025), in a life cycle assessment focused on the carbon–water–energy nexus, emphasize that water-related impacts, such as extraction, treatment, and process consumption, can be significant depending on the technology and local conditions. Different electrolysis technologies require varying volumes and quality levels of water, which can affect overall environmental performance. Therefore, even in regions with sufficient water availability, these factors must be carefully considered to ensure sustainable hydrogen production.

Social variables, e.g., the availability of a skilled workforce (1%) and the presence of hospitals (0.5%), tend to affect the operational phase of projects more than the initial site selection, serving primarily as supporting factors during later stages of implementation.

Analysis of the weights assigned in Minas Gerais revealed a prioritization pattern that differed from most international studies, indicating strong territorial-specific influences on the AHP decision-making structure. While studies such as (Ali, 2022; Amrani, 2024; Flora, 2025; Rekik, 2024) place greater emphasis on resource availability, particularly solar potential and, in some cases, water availability, the results for Minas Gerais show that environmental and regulatory factors dominate in defining territorial suitability. In the studies conducted in arid or semi-arid regions, maximizing the technical efficiency of electrolysis drives weight allocation, making natural resource availability the main factor distinguishing suitable from unsuitable areas.

AHP-based criterion weighting is generally derived from expert judgments using pairwise comparisons (Amrani, 2024; Pinto, 2025; Rekik, 2024; Rocha, 2023). This approach is widely applied because it leverages participants' technical knowledge and practical experience. However, some degree of subjectivity can arise, as experts naturally emphasize areas aligned with their own expertise. This limitation is inherent to the AHP method, since judgments are based on individual perceptions and can affect the final ranking of criteria and subcriteria.

To mitigate this issue, studies by (Amrani, 2024) and (Rekik, 2024) assess matrix consistency indices, while (Pinto, 2025) and (Rocha, 2023) employ additional strategies, including consulting multiple experts and comparing alternative decision matrices. Even with these measures, subjectivity cannot be completely eliminated. Consequently, results should be interpreted with this in mind, recognizing that the hierarchical ranking reflects a technical consensus that is nonetheless influenced by individual expert perspectives.

Production Potential Analysis

In the 66 microregions of Minas Gerais, the indicators used in the AHP model capture a wide range of geographical, environmental, economic, and social conditions. This diversity allows different pathways for developing the green hydrogen economy to be identified, tailored to the specific characteristics of each region.

Figure 6 illustrates the performance of each microregion with respect to the four main criteria defined in the AHP.

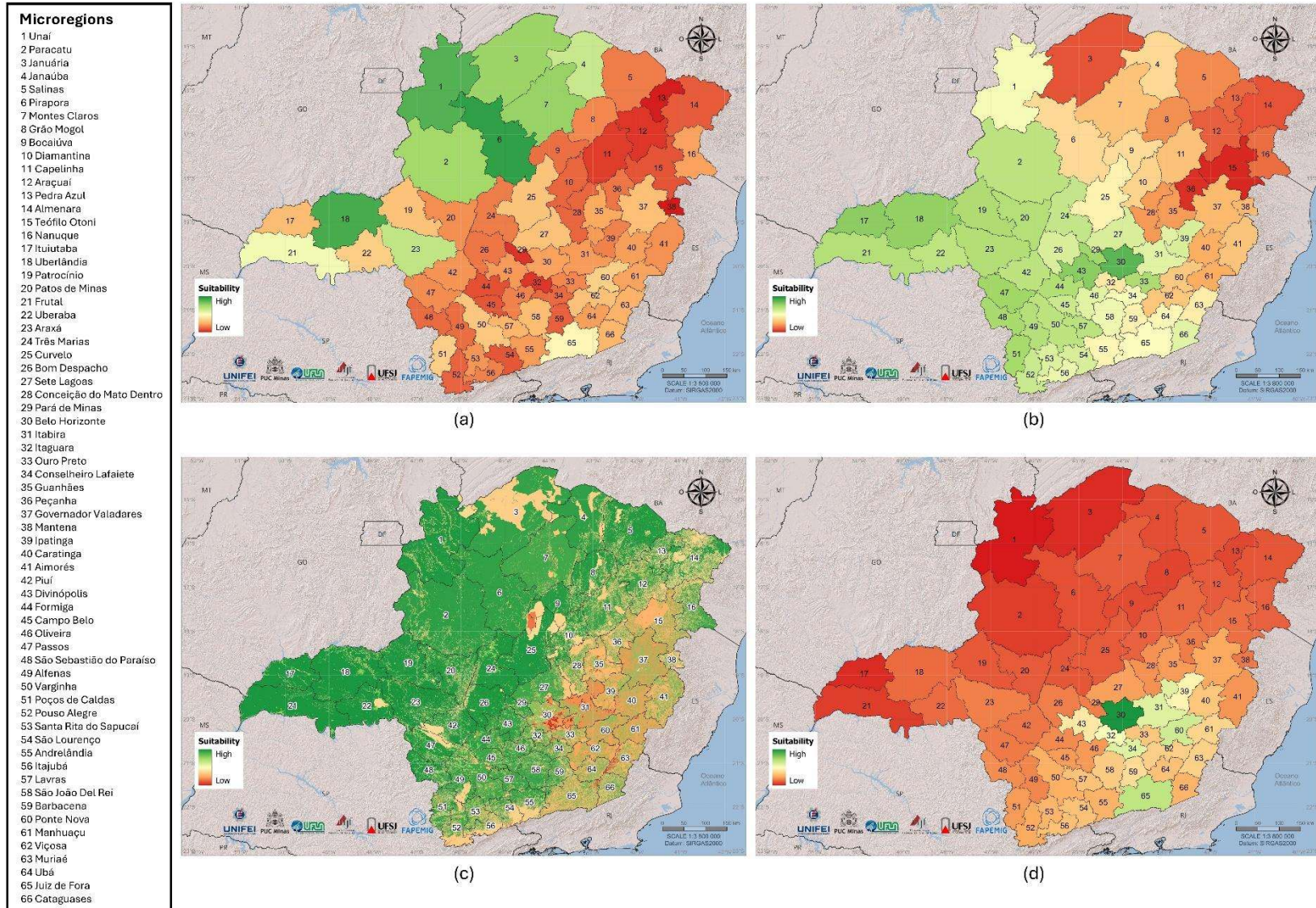


Figure 6 - Suitability Map for H2V Production – General Scenario per Criterion (a) Resources (b) Development (c) Environmental (d) Infrastructure

For the **Resource Availability** criterion, the microregions of Pirapora (6), Uberlândia (18), Unaí (1), Montes Claros (7), Januária (3), and other areas in northwestern Minas Gerais stand out. Their high performance is primarily due to abundant solar potential and moderate wind resources, with Global Horizontal Irradiation (GHI) values exceeding $5.4 \text{ kWh/m}^2 \cdot \text{d}$, and average wind speeds above 7 m/s .

For the **Development Aspects** criterion, the Belo Horizonte microregion, which includes the state capital, has the highest socioeconomic indicators in Minas Gerais. This region is the most urbanized in the state, concentrating a large share of industrial, commercial, and service activities, alongside the highest population densities. The southwest region also performs well, with some of the highest Human Development Index (HDI) values and a significant number of technical and higher education institutions. These factors enhance the training of qualified labor, stimulate innovation, and improve the structural conditions favorable for attracting new ventures.

For the **Environmental Aspects** criterion, higher suitability is observed in the *Triângulo Mineiro*, Northwest, and parts of northern Minas Gerais. These areas have lower proportions of restrictive zones, including Conservation Units, *quilombola*, and indigenous territories, as well as fewer slope-related limitations, facilitating project implementation. They are also characterized by low urban occupation, limited mining activity, and reduced exposure to flash floods, landslides, and flooding, further supporting their suitability for green hydrogen development. These characteristics explain why western and northwestern Minas Gerais stand out as regions with high suitability in terms of Environmental Aspects, as shown in Figure 6. In contrast, the central-eastern and southeastern parts of the state face greater environmental constraints due to rugged terrain, high urban density, significant mining activity, and elevated exposure to geological and hydrological risks, which reduce their relative suitability.

For the **Infrastructure Availability** criterion, many microregions in northern, northwestern, and northeastern Minas Gerais show low suitability. This reflects limited highway, railway, and pipeline density, as well as greater distances to ports. While these factors constrain the immediate feasibility of new projects, targeted investments in logistics and energy infrastructure could substantially enhance the potential of these regions to integrate into the green hydrogen value chain. Conversely, microregions like Belo Horizonte (30), Juiz de Fora (65), Ponte Nova (60), and Itabira (31) show higher suitability in this criterion. These areas benefit from well-established urban centers, higher population densities, and a history of substantial investment, resulting in more developed and robust infrastructure.

Figure 7 shows the comparative suitability map of the 66 microregions of Minas Gerais for green hydrogen (H_2V) production, considering all 22 subcriteria across their hierarchical levels. In this scenario, the highest-ranked microregions are Uberlândia (18), Pirapora (6), Araxá (23), Unaí (1), and Paracatu (2), in that order. Despite its statewide significance, the Metropolitan Region of Belo Horizonte ranks 31st in the model. Table 3 presents the ranking of the top twenty microregions in terms of comparative suitability for green hydrogen production.

- Microregions**
- 1 Unaí
 - 2 Paracatu
 - 3 Januária
 - 4 Janaúba
 - 5 Salinas
 - 6 Pirapora
 - 7 Montes Claros
 - 8 Grão Mogol
 - 9 Bocaiúva
 - 10 Diamantina
 - 11 Capelinha
 - 12 Araçuaí
 - 13 Pedra Azul
 - 14 Almenara
 - 15 Teófilo Otoni
 - 16 Nanuque
 - 17 Ituiutaba
 - 18 Uberlândia
 - 19 Patrocínio
 - 20 Patos de Minas
 - 21 Frutal
 - 22 Uberaba
 - 23 Araxá
 - 24 Três Marias
 - 25 Curvelo
 - 26 Bom Despacho
 - 27 Sete Lagoas
 - 28 Conceição do Mato Dentro
 - 29 Pará de Minas
 - 30 Belo Horizonte
 - 31 Itabira
 - 32 Itaguara
 - 33 Ouro Preto
 - 34 Conselheiro Lafaiete
 - 35 Guanhães
 - 36 Peçanha
 - 37 Governador Valadares
 - 38 Mantena
 - 39 Ipatinga
 - 40 Caratinga
 - 41 Aimorés
 - 42 Piuí
 - 43 Divinópolis
 - 44 Formiga
 - 45 Campo Belo
 - 46 Oliveira
 - 47 Passos
 - 48 São Sebastião do Paraíso
 - 49 Alfenas
 - 50 Varginha
 - 51 Poços de Caldas
 - 52 Pouso Alegre
 - 53 Santa Rita do Sapucaí
 - 54 São Lourenço
 - 55 Andrelândia
 - 56 Itajubá
 - 57 Lavras
 - 58 São João Del Rei
 - 59 Barbacena
 - 60 Ponte Nova
 - 61 Manhuaçu
 - 62 Viçosa
 - 63 Muriaé
 - 64 Ubá
 - 65 Juiz de Fora
 - 66 Cataguases

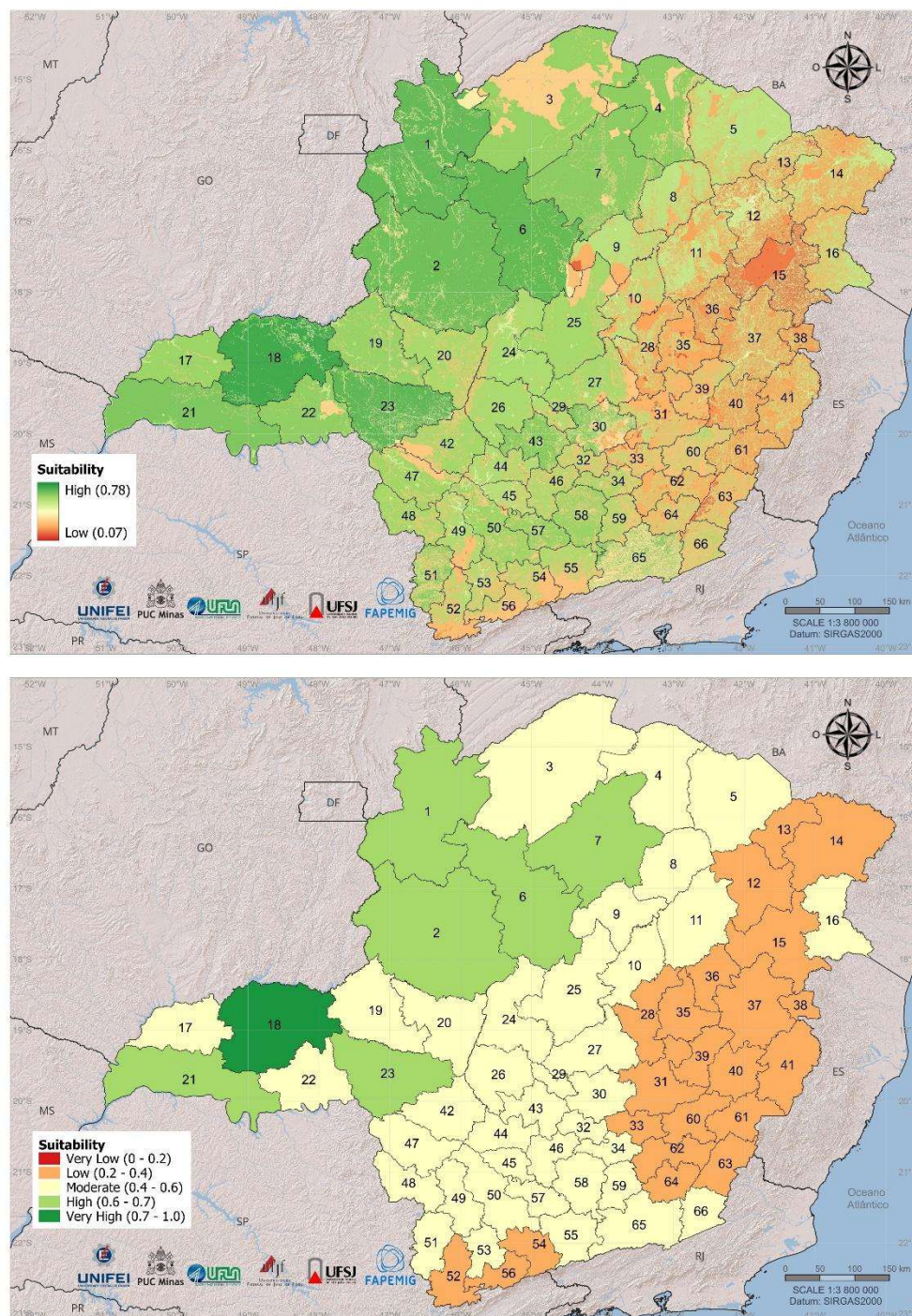


Figure 7 - Suitability Map for H2V Production – Scenario 1: General

Table 3 - Suitability of top-10 microregions in Minas Gerais for green hydrogen production, considering different configurations on Resources-based subcriteria.

	Scenario 1 General		Scenario 2 Wind resources		Scenario 3 Solar resources		Scenario 4 Biomass resources		Scenario 5 Water resources	
1°	Uberlândia	0.71	Uberlândia	0.76	Paracatu	0.68	Uberlândia	0.72	Uberlândia	0.71
2°	Pirapora	0.66	Frutal	0.69	Pirapora	0.67	Araxá	0.71	Araxá	0.68
3°	Araxá	0.65	Araxá	0.69	Unaí	0.67	Uberaba	0.67	Frutal	0.67
4°	Unaí	0.65	Patrocínio	0.65	Uberlândia	0.65	Patrocínio	0.66	Patrocínio	0.65
5°	Paracatu	0.64	Montes Claros	0.65	Frutal	0.64	Frutal	0.66	Ituiutaba	0.64
6°	Frutal	0.64	Pirapora	0.64	Janaúba	0.62	Paracatu	0.65	Paracatu	0.63
7°	Montes Claros	0.61	Uberaba	0.64	Araxá	0.62	Ituiutaba	0.65	Uberaba	0.63
8°	Ituiutaba	0.60	Ituiutaba	0.63	Montes Claros	0.60	Divinópolis	0.63	Divinópolis	0.62
9°	Uberaba	0.60	Divinópolis	0.61	Ituiutaba	0.60	Unaí	0.62	Bom Despacho	0.61
10°	Patrocínio	0.59	Unaí	0.60	Divinópolis	0.60	Bom Despacho	0.62	Unaí	0.61

Table 4 - Suitability of top-10 microregions in Minas Gerais for green hydrogen production, considering different configurations on criteria.

	Scenario 1 General		Scenario 6 Bahia -based		Scenario 7 Egalitarian-based		Scenario 8 Resources-based		Scenario 9 Infrastructure-based		Scenario 10 Environmental- based		Scenario 11 Development-based	
1°	Uberlândia	0.71	Uberlândia	0.62	Uberlândia	0.61	Uberlândia	0.60	Belo Horizonte	0.72	Uberlândia	0.75	Belo Horizonte	0.72
2°	Pirapora	0.66	Araxá	0.56	Belo Horizonte	0.61	Pirapora	0.53	Juiz de Fora	0.54	Frutal	0.70	Uberlândia	0.68
3°	Araxá	0.65	Pirapora	0.55	Divinópolis	0.56	Unaí	0.53	Divinópolis	0.50	Araxá	0.70	Divinópolis	0.65
4°	Unaí	0.65	Paracatu	0.55	Araxá	0.56	Paracatu	0.52	Conselheiro Lafaiete	0.49	Paracatu	0.68	Araxá	0.62
5°	Paracatu	0.64	Unaí	0.55	Paracatu	0.54	Araxá	0.51	Ponte Nova	0.46	Ituiutaba	0.68	Ituiutaba	0.62
6°	Frutal	0.64	Frutal	0.52	Frutal	0.53	Frutal	0.47	Itabira	0.46	Divinópolis	0.68	Frutal	0.60
7°	Montes Claros	0.61	Belo Horizonte	0.50	Ituiutaba	0.51	Montes Claros	0.46	Uberlândia	0.44	Uberaba	0.67	Paracatu	0.60
8°	Ituiutaba	0.60	Divinópolis	0.50	Lavras	0.51	Belo Horizonte	0.45	Itaguara	0.44	Patrocínio	0.67	Patrocínio	0.59
9°	Uberaba	0.60	Montes Claros	0.50	Unaí	0.50	Janaúba	0.43	Lavras	0.43	Unaí	0.66	Passos	0.58
10°	Patrocínio	0.59	Uberaba	0.48	Uberaba	0.50	Juiz de Fora	0.43	São João Del Rei	0.42	Pirapora	0.65	Poços de Caldas	0.58

A strong correspondence is observed between the model results and real-world industrial and policy developments in Minas Gerais. The roadmap developed by CEMIG highlights the state's potential to become a national hub for green hydrogen (H₂V) production and proposes a distributed, multi-hub cluster model integrating production, consumption, and infrastructure (CEMIG, 2025). In addition, Araxá and Paracatu are located within large-scale mining-based industrial regions characterized by the concentration of mineral extraction and processing activities, particularly associated with niobium and gold production, respectively. Araxá hosts one of the world's largest niobium production complexes operated by CBMM (CBMM, 2024), while Paracatu is home to large-scale gold mining operations led by Kinross Gold Corporation (KINROSS GOLD CORPORATION, 2023). These mining-intensive regions are recognized for their high energy demand and strong potential for industrial decarbonization through hydrogen integration. Meanwhile, Uberlândia and Unai benefit from strategic logistics and agribusiness corridors, reinforcing their role as prospective hydrogen distribution and demand hubs. These patterns are consistent with national and regional frameworks, including the Brazilian National Hydrogen Program (MME, 2021), initiatives promoted by FIEMG (FIEMG – FEDERAÇÃO DAS INDÚSTRIAS DO ESTADO DE MINAS GERAIS, 2023), and the Ten-Year Energy Expansion Plan by EPE (EPE, 2024), thereby reinforcing the policy coherence and practical relevance of the proposed model.

Building upon these alignments, the results provide strategic insights for policymaking and regional planning in Minas Gerais. The identification of high-suitability areas offers a scientific basis for prioritizing investments, guiding infrastructure deployment, and fostering the development of green hydrogen hubs. Consequently, the proposed framework serves as a robust decision-support tool for governments, industry stakeholders, and investors, contributing to the efficient allocation of resources and the sustainable expansion of the green hydrogen economy.

A clear spatial pattern emerged among the highest-ranked microregions, primarily concentrated in the northwest of Minas Gerais. This region stands out due to fewer restricted areas, minimal land use and occupation limitations, and lower exposure to risk zones, which favors the establishment of new projects and explains its superior performance in the AHP model.

The results indicate that overall suitability scores at the microregional level do not exceed an average of 0.71, with a maximum of 0.78 observed in certain areas within these regions. The difference between the most suitable microregion (0.71) and the least suitable (0.26) is approximately 60%, highlighting the significant variability in conditions across the state.

Moreover, starting from the seventh-ranked microregion, suitability values differ by more than 10%, showing that the top six microregions have very similar suitability levels.

Using the final land suitability map from the AHP model, continuous values were grouped into five suitability categories (Figure 7).

It is important to note that the 'very high' suitability class begins at 0.7, since the model's maximum value did not exceed 0.78.

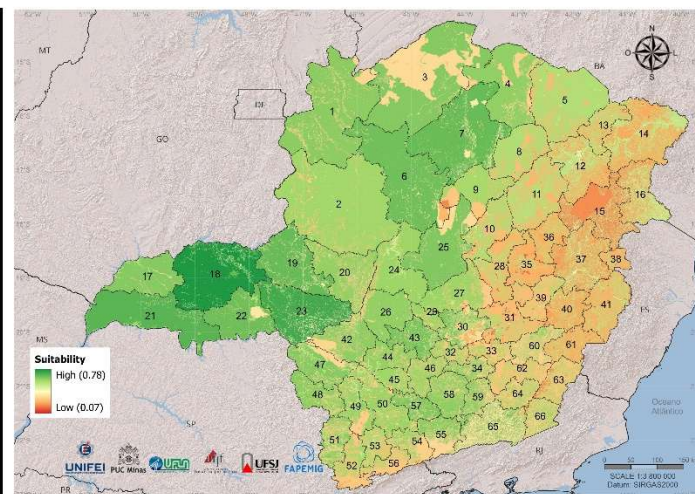
Overall, 40.1% of Minas Gerais shows high suitability for green hydrogen production, while areas with very high suitability cover only 2.9% of the state. Regions of moderate suitability cover 26.3% of the

territory. The lowest suitability classes comprise 28.8% of the state with low suitability and only 2.0% with very low suitability, primarily due to steep terrain and the presence of restricted-use areas.

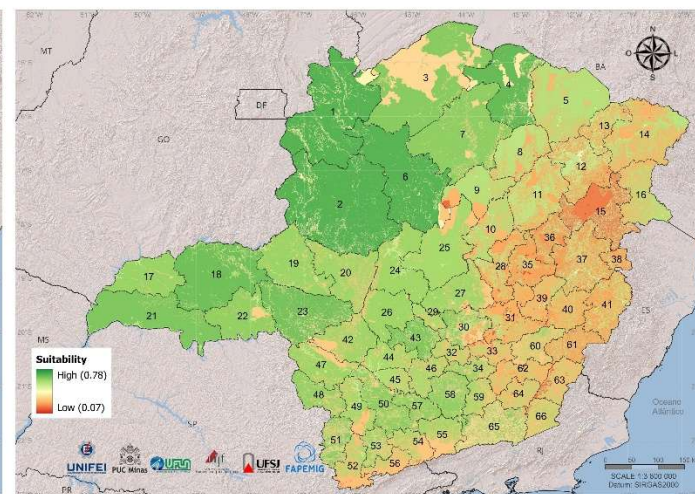
3.3. Suitability analysis per scenario

Figure 8 shows territorial suitability for green hydrogen production under specific technological routes: Scenario 2 (wind resources), Scenario 3 (solar resources), and Scenario 4 (biomass and waste).

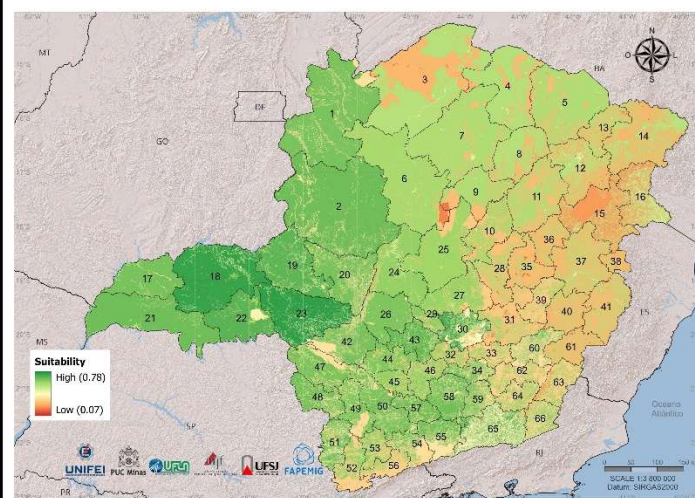
- Microregions**
- 1 Unaí
 - 2 Paracatu
 - 3 Januária
 - 4 Janaúba
 - 5 Salinas
 - 6 Pirapora
 - 7 Montes Claros
 - 8 Grão Mogol
 - 9 Bocaiúva
 - 10 Diamantina
 - 11 Capelinha
 - 12 Araçuaí
 - 13 Pedra Azul
 - 14 Almenara
 - 15 Teófilo Otoni
 - 16 Nanuque
 - 17 Ituiutaba
 - 18 Uberlândia
 - 19 Patrocínio
 - 20 Patos de Minas
 - 21 Frutal
 - 22 Uberaba
 - 23 Araxá
 - 24 Três Marias
 - 25 Curvelo
 - 26 Bom Despacho
 - 27 Sete Lagoas
 - 28 Conceição do Mato Dentro
 - 29 Pará de Minas
 - 30 Belo Horizonte
 - 31 Itabira
 - 32 Itaguara
 - 33 Ouro Preto
 - 34 Conselheiro Lafaiete
 - 35 Guanhães
 - 36 Pegañha
 - 37 Governador Valadares
 - 38 Mantena
 - 39 Ipatinga
 - 40 Caratinga
 - 41 Almorés
 - 42 Pium
 - 43 Divinópolis
 - 44 Formiga
 - 45 Campo Belo
 - 46 Oliveira
 - 47 Passos
 - 48 São Sebastião do Paraíso
 - 49 Alfenas
 - 50 Varginha
 - 51 Poços de Caldas
 - 52 Pouso Alegre
 - 53 Santa Rita do Sapucaí
 - 54 São Lourenço
 - 55 Andrelândia
 - 56 Itajubá
 - 57 Lavras
 - 58 São João Del Rei
 - 59 Barbacena
 - 60 Ponte Nova
 - 61 Manhuaçu
 - 62 Viçosa
 - 63 Muriaé
 - 64 Ubá
 - 65 Juiz de Fora
 - 66 Cataguases



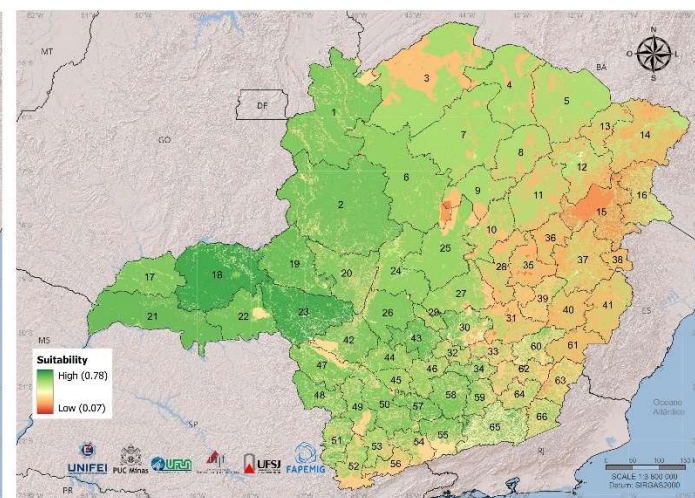
(a)



(b)



(c)



(d)

Figure 8 - Suitability Map for H2V Production – (a) Scenario 2: Wind Energy and Water Resources (b) Scenario 3: Solar Energy and Water Resources (c) Scenario 4: Biomass and Water Resources (d) Scenario 5: Water Resources

The results show strong agreement across the three scenarios. Microregions including Uberlândia (18), Araxá (23), Uberaba (22), Frutal (21), Patrocínio (19), and Paracatu (2) consistently rank among the top, regardless of the technological route, as shown in Table 3 (AHP Results – Scenarios 2, 3, 4 and 5). Uberlândia, in particular, performs best in the wind-hydro and biomass-hydro scenarios and ranks among the top microregions in the solar-hydro scenario, and also ranks first in the scenario that assigns greater importance to water resources. This consistency underscores the robustness of these regions in terms of territorial suitability for green hydrogen production.

The consistent suitability is explained by structural factors such as strong solar radiation (over 5.4 kWh/m²·day), average wind speeds above 7 m/s, and plentiful biomass and municipal waste resources. Additionally, the low proportion of environmentally restricted areas, favorable topography, and contributions from the other subcriteria of the model collectively support the high performance of these microregions, independent of the energy resource considered.

Differences are more apparent in the mid-ranked microregions. For example, São João Del Rei (58) ranks 12th with biomass, but only 16th with solar and 19th with wind. These differences highlight the spatial sensitivity of certain regions to specific resource availability, reflecting variations in local wind conditions, solar radiation, and biomass potential.

Likewise, Pirapora (6) and Montes Claros (7) rank high in the solar and wind scenarios, respectively, but have lower scores in the biomass scenario. This reflects local differences in the distribution of energy resources. While the model identifies structurally robust territorial cores for green hydrogen production, these variations in intermediate rankings underscore the importance of route-specific analyses, particularly for informing regional energy planning strategies.

In general, the microregions of Uberlândia (18), Araxá (23), and Paracatu (2) are consistently ranked among the top ten most suitable microregions for green hydrogen production across all evaluated scenarios (see Tables 3 and 4). Their repeated presence at the top of the rankings indicates that their high suitability is not driven by a specific weighting configuration, but rather by a consolidated set of favorable territorial conditions. The only exception is Scenario 9, in which infrastructure-related criteria gain greater relevance; even in this case, Uberlândia remains within the top ten, ranking seventh. The results of Scenario 6, based on the Bahia Green Hydrogen Atlas (Governo do Estado da Bahia, 2023) criteria, closely match the other scenarios in highlighting priority microregions for green hydrogen production in Minas Gerais. The accuracy map (Figure 9) confirms that the primary areas of suitability are concentrated in the *Triângulo Mineiro* and Northwest Minas Gerais regions.

Microregions	
1	Unaí
2	Paracatu
3	Januária
4	Janaúba
5	Salinas
6	Pirapora
7	Montes Claros
8	Grão Mogol
9	Bocaiúva
10	Diamantina
11	Capelinha
12	Araçuaí
13	Pedra Azul
14	Almenara
15	Teófilo Otoni
16	Nanuque
17	Ituiutaba
18	Uberlândia
19	Patrocínio
20	Patos de Minas
21	Frutal
22	Uberaba
23	Araxá
24	Três Marias
25	Curvelo
26	Bom Despacho
27	Sete Lagoas
28	Conceição do Mato Dentro
29	Pará de Minas
30	Belo Horizonte
31	Itabira
32	Itaguara
33	Ouro Preto
34	Conselheiro Lafaiete
35	Guanhães
36	Peçanha
37	Governador Valadares
38	Mantena
39	Ipatinga
40	Caratinga
41	Aimorés
42	Piuiú
43	Divinópolis
44	Formiga
45	Campo Belo
46	Oliveira
47	Passos
48	São Sebastião do Paraíso
49	Alfenas
50	Varginha
51	Poços de Caldas
52	Pouso Alegre
53	Santa Rita do Sapucaí
54	São Lourenço
55	Andrelândia
56	Itajubá
57	Lavras
58	São João Del Rei
59	Barbacena
60	Ponte Nova
61	Manhuaçu
62	Viçosa
63	Muriae
64	Ubá
65	Juiz de Fora
66	Cataguases

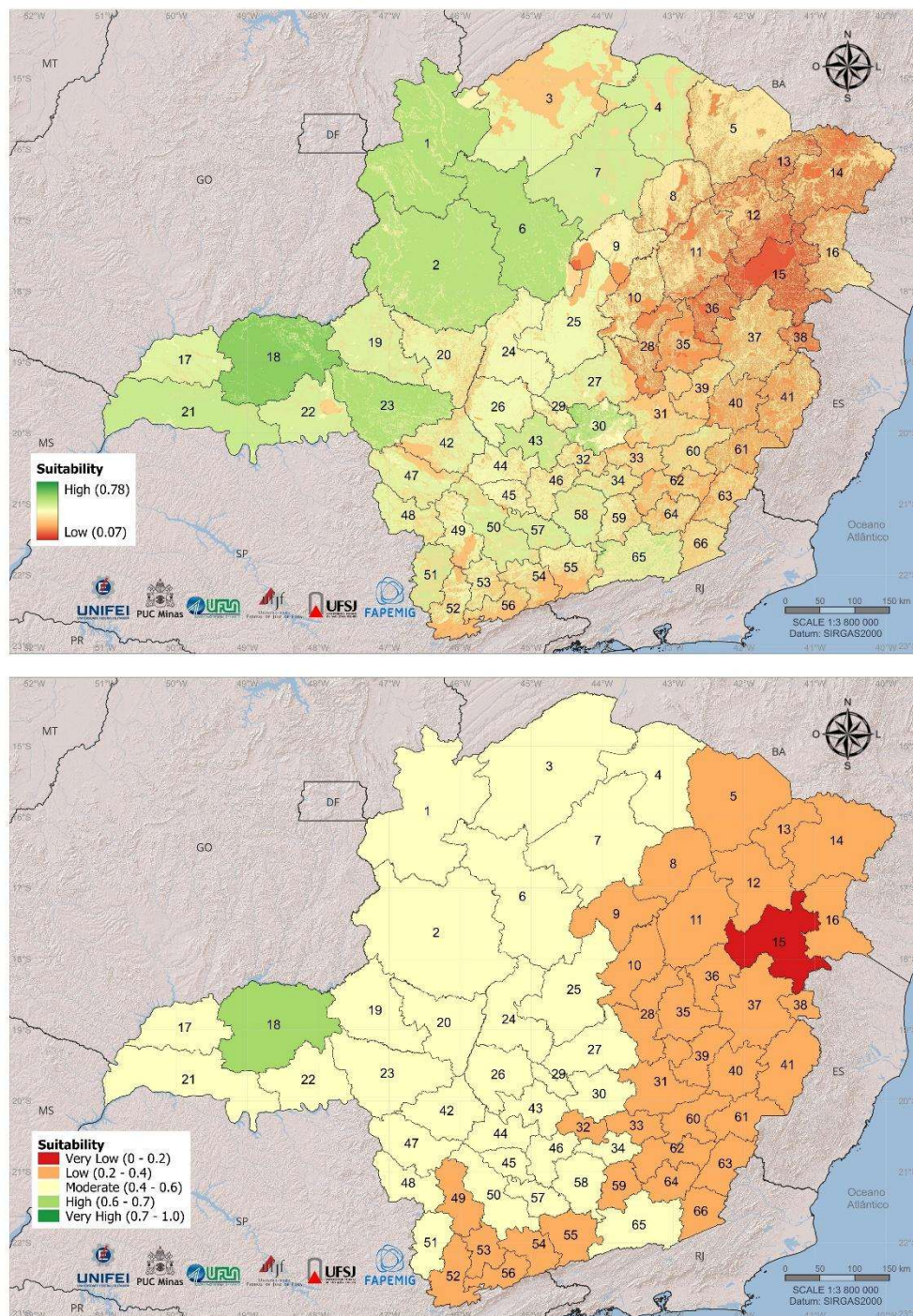


Figure 9 - Suitability Map for H2V Production of Scenario 6: Weights from Bahia

In Scenario 6, 58.63% of the assessed area is classified as having moderate suitability, followed by 36.10% with low suitability, 3.17% with high suitability, and only 1.99% with very low suitability, reinforcing the predominance of areas with favorable conditions across the study region.

Even when Resource Availability or Environmental Aspects are given greater weight, the ranking of regions stays mostly the same. This demonstrates that these priority microregions perform

well across both environmental and resource criteria, ensuring their stability in the rankings regardless of the weighting emphasis applied.

Territorial assessments of green hydrogen production potential

Minas Gerais has an estimated green hydrogen potential of 46.1 Mt, mostly from solar (86%), then wind (13%), and a small share from biomass and waste (less than 1%, with waste at 0.4%). It is important to note that both solar and wind potential were calculated using only 10% of the available area, whereas biomass potential assumes full utilization of agricultural residues and biogas from municipal solid waste and animal effluents.

Minas Gerais's green hydrogen potential is much higher than Brazil's current and future domestic demand (400 kt/year today, 630 kt/year by 2030) and the expected export volume of about 800 kt in 2030 (Siffert; Rocha, 2025). Remarkably, this potential corresponds to roughly half of current global hydrogen demand, estimated at 100 Mt (IEA, 2025).

The solar photovoltaic potential for electricity, and thus hydrogen production, is consistent with values cited in literature, particularly in northern Minas Gerais. The wind potential, considered only in areas with average speeds above 7.0 m/s at 150 m height, could generate approximately 340 TWh/year, corresponding to 6.2 Mt H₂. For comparison, the Minas Gerais Wind Atlas (CEMIG, 2012) estimated generation of around 90 TWh/year for parks with 3.0 MW turbines (>7.0 m/s at 100 m), while respecting environmental restrictions such as conservation units. Wind potential can vary significantly depending on factors like turbine layout and land-use density (MW/km²). Using the density reported in the Minas Gerais Wind Atlas (1.5 MW/km²) or the Brazilian Wind Potential Atlas (Amarante et al., 2001) (2.0 MW/km²), estimated electricity generation would decrease to 127.6 TWh (2.3 Mt H₂) and 170.2 TWh (3.1 Mt H₂), respectively. The biomass potential was estimated at 14.7 TWh (0.3 Mt H₂), with about 10 TWh coming from biogas produced from animal waste, especially cattle effluent (7.1 TWh). For context, electricity consumption in Minas Gerais in 2024 totaled 67.5 TWh, with the industrial sector accounting for 35.4 TWh and the residential sector for 15.4 TWh (EPE, 2025).

Comparing territorial suitability with the hydrogen production potential of each microregion revealed areas of both agreement and discrepancy. In general, regions classified as high or very high suitability also show elevated hydrogen generation potential. As shown in Figure 10, the northwestern microregions, which account for roughly 35% of potential hydrogen production, correspond to areas with high AHP scores (greater than 0.6). Unlike other regions, Uberaba (22) has moderate suitability and low potential but is the site of the H2X Minas Gerais project (H2Brasil, 2025). Once fully operational in 2030, the project will feature approximately 820 MW of installed electrolysis capacity powered by renewable sources, with an estimated annual production of 124 kt H₂ and 689 kt of ammonia, supported by a total investment of around USD 1.39 billion.

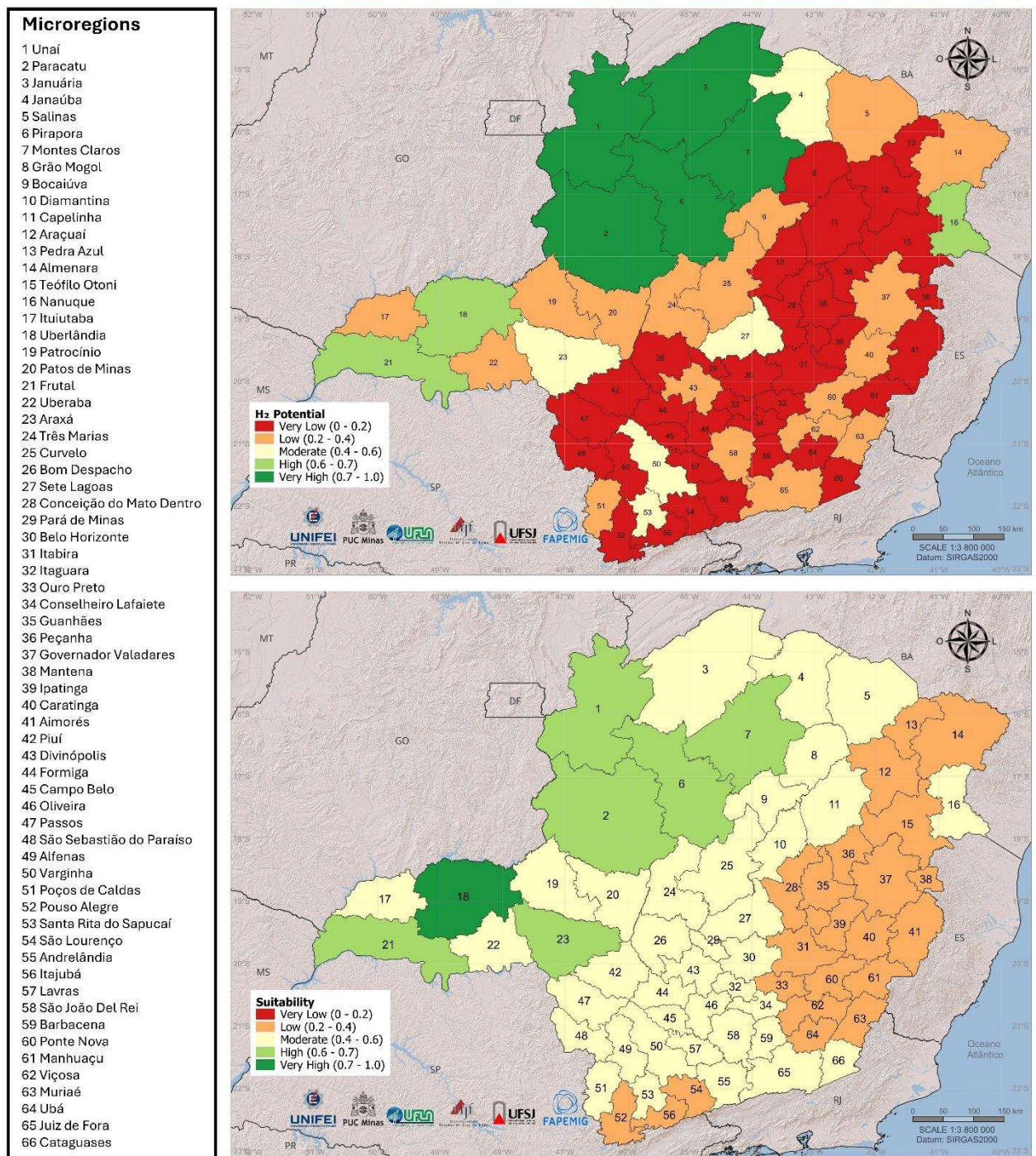


Figure 10 - Suitability (Scenario 1) and potential for green hydrogen production in Minas Gerais (Brazil), normalized values (AHP: 0.26-0.71; Potential: 0.07-3.34 MtH₂).

Figure 11 shows a strong territorial alignment between the two approaches, i.e., regions with the highest AHP scores generally correspond to areas with significant hydrogen production potential. In Figure 11, labeled points indicate the five microregions with the highest AHP scores and the five microregions with the greatest production potential. In these regions, even small changes in suitability (up to 10%) can lead to significant differences in production potential (Scenario 1). For instance, Araxá

(Region 2) has a potential of 3.34 Mt, while Region 18, which has the highest suitability, has a potential of 2.21 Mt. Januária (Region 3) is particularly noteworthy, and despite its considerable potential (1.31 Mt H₂/year), it ranks 27th in suitability due to environmental restrictions and land-use constraints. Approximately 60% of this microregion is limited by conservation units, indigenous territories, and steep slopes. Nevertheless, its high solar resource availability (5.4 kWh/m²·day) drives its elevated hydrogen production potential.

Under the alternative weighting scheme (Scenario 6), where Resource Availability is given more weight than Environmental Aspects, the same key regions identified in Scenario 1 continue to dominate. A similar spatial profile and comparable range of AHP scores are observed between the two scenarios. However, the magnitude of the scores is lower under Scenario 6, ranging from 0.19 to 0.62, compared with 0.26 to 0.71 in Scenario 1. As mentioned, these differences reflect evaluator perspectives, i.e., Scenario 1 emphasizes environmental constraints in energy system implementation, while Scenario 6 gives priority to resource availability. Because resource potential originates from multiple sources, solar, wind, and biomass, it was consolidated in the prioritization process in terms of electricity generation potential. Given that solar and wind resources dominate in potential and are strongly influenced by territorial availability, the overall similarity between Scenarios 1 and 5 is expected.

In the other scenarios, which consider only a single resource, the regions leading in both suitability and production potential remain largely unchanged. The only exceptions were in Regions 19 (Patrocínio), 21 (Frutal), and 22 (Uberaba), all located in the same western mesoregion, which show high suitability when only biomass resources are considered (Scenario 4). In Scenario 3, which considers only solar resources, the regional pattern closely matches that of Scenario 1. By contrast, Scenario 2, which focuses exclusively on wind resources, shows a different pattern. Some regions that are highly suitable in other scenarios, such as Region 2 (Paracatu), do not meet the minimum average wind speed of 7.0 m/s assumed for viable wind exploitation in this study, limiting their potential under this scenario.

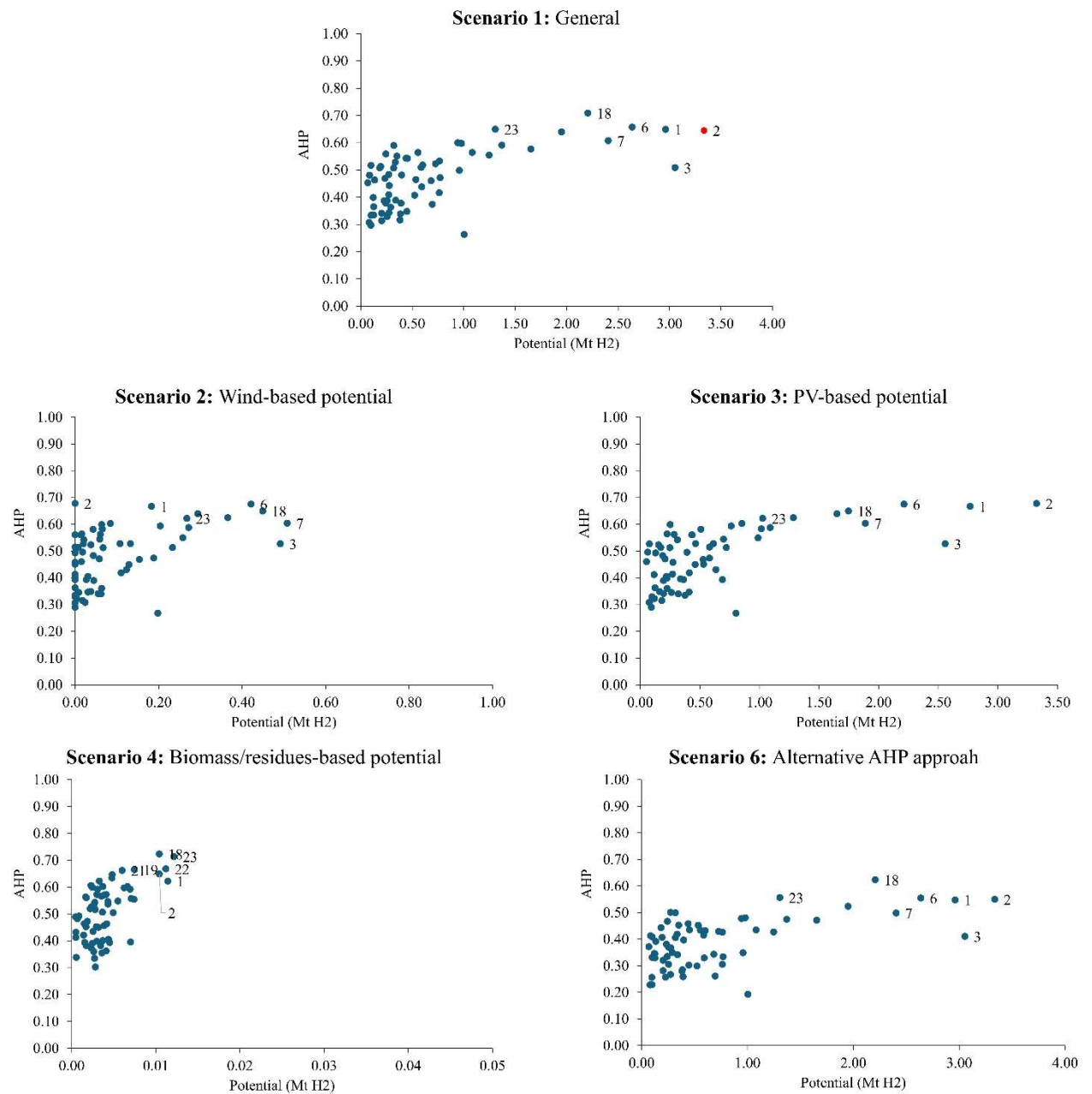


Figure 11 - Suitability by AHP scores and potential for green hydrogen production in Minas Gerais (Brazil).

2.4. Conclusions

This study evaluated and compared territorial suitability and green hydrogen production potential across the 66 microregions of Minas Gerais, Brazil. Territorial suitability was evaluated using the AHP method, based on 22 subcriteria encompassing resource availability, environmental aspects, development, and infrastructure. Production potential was estimated for hydrogen generated via water electrolysis, considering electricity from wind, solar photovoltaic, and biomass and waste sources.

In the AHP analysis based on the interviews, the 'restricted areas' sub-criterion was the most influential, followed by 'risk areas' and 'land use and occupation'. This finding suggests that legal and environmental constraints play a more significant role in determining territorial suitability than the availability of energy resources themselves. Microregions in the *Triângulo Mineiro* and the Northwest/West of Minas Gerais, particularly Uberlândia, Paracatu, Pirapora, Unaí, and Araxá, consistently ranked among the most suitable across the different scenarios analyzed. This performance reflects favorable conditions e.g., abundant renewable energy resources, limited restrictions, and suitable topography.

The recurring presence of these microregions among the top rankings highlights the robustness of the results, indicating that minor variations in criteria or resource availability do not substantially affect the identified spatial pattern. Scenarios considering only solar, wind, or biomass energy converged on the same group of microregions with higher territorial suitability. By contrast, some intermediate microregions, such as São João Del Rei, Pirapora, and Montes Claros, showed greater sensitivity to changes in the resources considered, underscoring the importance of assessing multiple energy pathways. Overall, 40.1% of Minas Gerais' territory was classified as highly suitable for green hydrogen production, while 2.9% was categorized as very highly suitable, revealing both areas with strong potential and regions facing limitations, mainly due to slope gradients, urbanization, and the presence of protected areas.

The results show that Minas Gerais has a technical green hydrogen potential of 46.1 Mt, far exceeding projected national demand, even under conservative land-use assumptions. Solar resources dominate, followed by wind power, underscoring the strategic role of these energy sources in the state. The combined analysis of territorial suitability and production potential generally shows spatial convergence, but also reveals cases where high production potential does not correspond to high territorial suitability. These findings emphasize that the development of green hydrogen relies not only on energy availability but also on integrated planning that considers territorial, environmental, and institutional dimensions, thereby promoting more realistic and sustainable decision-making.

In this context, the results also align with emerging national and state-level policy frameworks for green hydrogen development in Brazil and Minas Gerais, reinforcing their relevance for supporting long-term energy planning and investment strategies.

Appendix

The Supplementary Material can be accessed through the following link: <https://docs.google.com/document/d/1gY6umnOXpMr4y6P6BJlqsOj2EeFaFT2O/edit?usp=sharing&oid=102329375988361574211&rtpof=true&sd=true>

3 Spatially Explicit Life Cycle Assessment of International Green Hydrogen Supply Chains for Stationary Electricity Generation

This manuscript has been submitted to a peer-reviewed journal for publication.

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Abstract

This study applies a spatially explicit Life Cycle Assessment (LCA) to evaluate the environmental performance of green hydrogen and its most promising hydrogen-derived fuels for stationary power generation. The assessment integrates the complete supply chain, from renewable hydrogen production in Minas Gerais, Brazil, to conversion into compressed hydrogen, liquefied hydrogen, ammonia, and methanol, international export to Europe, and final use in dual-fuel compression ignition engines for electricity generation. Considering wheel-to-well boundaries and ReCiPe 2016 Midpoint (H) method, 1 kWh of generated electricity was evaluated across global warming, fossil resource scarcity, air quality, human toxicity, and ecotoxicity indicators. HVO-based scenarios showed the best overall environmental performance, reducing global warming impacts by approximately 85% compared with diesel while maintaining low impacts across most categories. Among the hydrogen pathways, biomass-powered electrolysis achieved the lowest global warming and fossil resource impacts, whereas photovoltaic-powered electrolysis performed best regarding toxicity and air quality. Methanol and ammonia presented important environmental trade-offs, with methanol increasing toxicity-related impacts and ammonia increasing fine particulate matter formation and offsetting climate benefits because of N₂O emissions during engine operation. Overall, the results highlight the importance of evaluating hydrogen and hydrogen-derived fuels across the entire supply chain to support sustainable fuel selection for stationary power generation.

Keywords: Hydrogen; CI engine; Emissions; Life cycle assessment.

3.1. Introduction

The increasing need to reduce greenhouse gas (GHG) emissions has positioned green hydrogen as a key energy vector for decarbonizing hard-to-electrify sectors while improving the flexibility of renewable-based energy systems. Produced through water electrolysis powered by renewable electricity, green hydrogen has become a central component of international decarbonization strategies (IEA, 2023). Regions with abundant renewable resources, such as South America, North Africa, the Middle East, and Australia, are considered promising locations for large-scale green hydrogen production because of their potential for low-cost renewable electricity (Alanazi et al., 2025).

Within the European energy transition, renewable hydrogen is expected to play a strategic role in sectors where direct electrification remains technically or economically challenging, including steel, chemicals, fertilizers, heavy transport, shipping, aviation, and stationary power generation (European Commission, 2020). Although electrification is advancing, diesel engines continue to dominate several of these applications, particularly in heavy-duty transport, off-road machinery, agriculture, mining,

marine systems, and distributed electricity generation (Eurostat, 2025). Consequently, renewable hydrogen has emerged as a promising pathway for reducing emissions while maintaining the operational flexibility required in these sectors.

Despite its environmental potential, the widespread use of hydrogen is limited by its low volumetric energy density, which complicates storage, transportation, and long-distance distribution. Consequently, hydrogen-derived fuels such as ammonia (NH_3) and methanol (MeOH) have gained increasing attention as alternative energy carriers. Ammonia is widely recognized as an efficient hydrogen carrier because of its high hydrogen density and well-established transportation infrastructure, whereas methanol is a liquid fuel under ambient conditions, facilitating storage, handling, and compatibility with existing fuel infrastructure and internal combustion engines. Both fuels are therefore regarded as promising options for long-distance hydrogen transport and stationary power Generation (Mekonnen et al., 2025; Negro; Noussan; Chiaramonti, 2023).

Among the available end-use technologies, dual-fuel compression-ignition engines provide a practical pathway for introducing hydrogen and hydrogen-derived fuels into existing energy systems. In these engines, hydrogen or hydrogen-derived fuels partially replace the primary diesel-type fuel while combustion is initiated by a pilot injection of diesel or hydrotreated vegetable oil (HVO). This configuration preserves the reliability and maturity of conventional compression-ignition technology while requiring only limited hardware modifications, facilitating the transition toward lower-carbon energy systems (Domínguez et al., 2023; Pinto et al., 2023b; Rodríguez-Fernández et al., 2024). Besides stationary electricity generation, similar engine technologies are widely employed in heavy-duty vehicles, off-road machinery, agriculture, mining, and marine applications (Rueda-Vázquez et al., 2024), extending the relevance of their environmental assessment beyond the power sector.

As hydrogen supply chains expand, evaluating their environmental performance from production to final use becomes increasingly important. Spatially explicit Life Cycle Assessment (LCA) has emerged as a valuable approach because it captures regional differences in renewable resource availability, electricity generation, infrastructure, and transportation logistics that cannot be adequately represented using conventional national-average inventories (Shi; Yan, 2024). Recent studies have shown that incorporating spatial information improves inventory representativeness, hotspot identification, and decision-making for sustainable energy planning (Ajlouni et al., 2026; Schomberg et al., 2022).

Although numerous studies have assessed renewable hydrogen production or specific hydrogen transport pathways, relatively few have integrated regionalized hydrogen production, conversion into hydrogen carriers, international transportation, and final use in internal combustion engines within a single LCA framework. This limitation makes it difficult to compare the environmental performance of alternative hydrogen supply chains under consistent assumptions.

To address this gap, this study applies a spatially explicit LCA to evaluate green hydrogen produced in previously identified suitable regions of Minas Gerais, Brazil (Goulart et al., 2026). Beyond the production stage, the analysis includes hydrogen exports from Brazil to Spain and its use in stationary internal combustion engines for electricity generation, using data derived from operational simulations. Europe was selected as the destination because it represents one of the most promising future markets for imported green hydrogen (European Commission, 2022), while Spain was adopted as a representative case study due to its strategic role as one of the continent's leading renewable hydrogen hubs. By evaluating the complete supply chain, from renewable hydrogen production to final electricity generation, this study provides a more comprehensive and realistic assessment of the environmental implications associated with implementing these energy carriers in stationary power generation.

3.2. Methodology

Scope

The LCA was performed using the OpenLCA software program, in conjunction with the Ecoinvent 3.6 database (Ecoinvent, 2019), while environmental impacts were assessed employing the ReCiPe 2016 Midpoint (H) method (Huijbregts et al., 2017).

A Wheel-to-wheel approach was used to conduct the analyses, covering all stages from hydrogen and hydrogen-derivative production, e.g., ammonia and methanol, to final use in internal combustion engines (ICE) for electricity generation, using 1.0 kWh as the functional unit.

The system boundaries included producing, conditioning, storing, internationally transporting, and finally, using the evaluated fuels for electricity generation in ICEs. Figure 12 presents the four analyzed scenarios, which include different export routes for green hydrogen produced in Minas Gerais and its application in dual-fuel systems operating with fossil diesel and hydrotreated vegetable oil (HVO) as diesel-type fuels (directly injected) and methanol (MeOH), ammonia (NH₃) or hydrogen (H₂) as replacing sustainable fuels (port fuel injected).

The microregions of *Paracatu* and *Uberlândia*, located in western Minas Gerais, Brazil, were previously identified as promising areas for green hydrogen production in Minas Gerais, based on their resource availability, infrastructure, environmental constraints, and socioeconomic factors (Goulart et al., 2026). Figure 13 shows the locations of these regions, the industrial facilities considered for CO₂ capture, and the Port of Santos. Accordingly, hydrogen production via electrolysis was evaluated in these two regions. In *Paracatu*, hydrogen was produced using photovoltaic (PV) energy, while in *Uberlândia* it was produced using wind (W) and biomass (B).

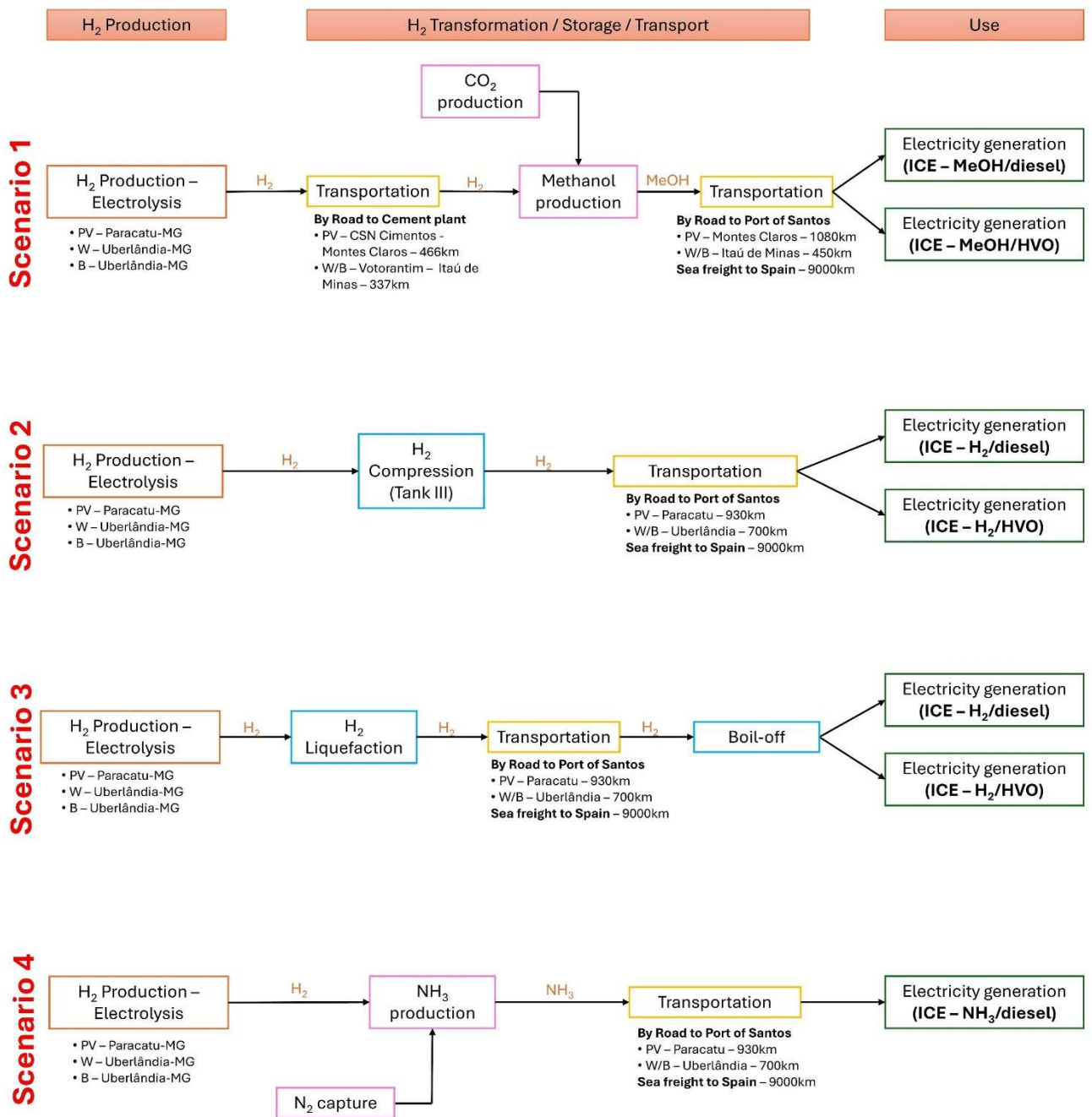


Figure 12 - Life cycle assessment (LCA) scenarios evaluated in this study.

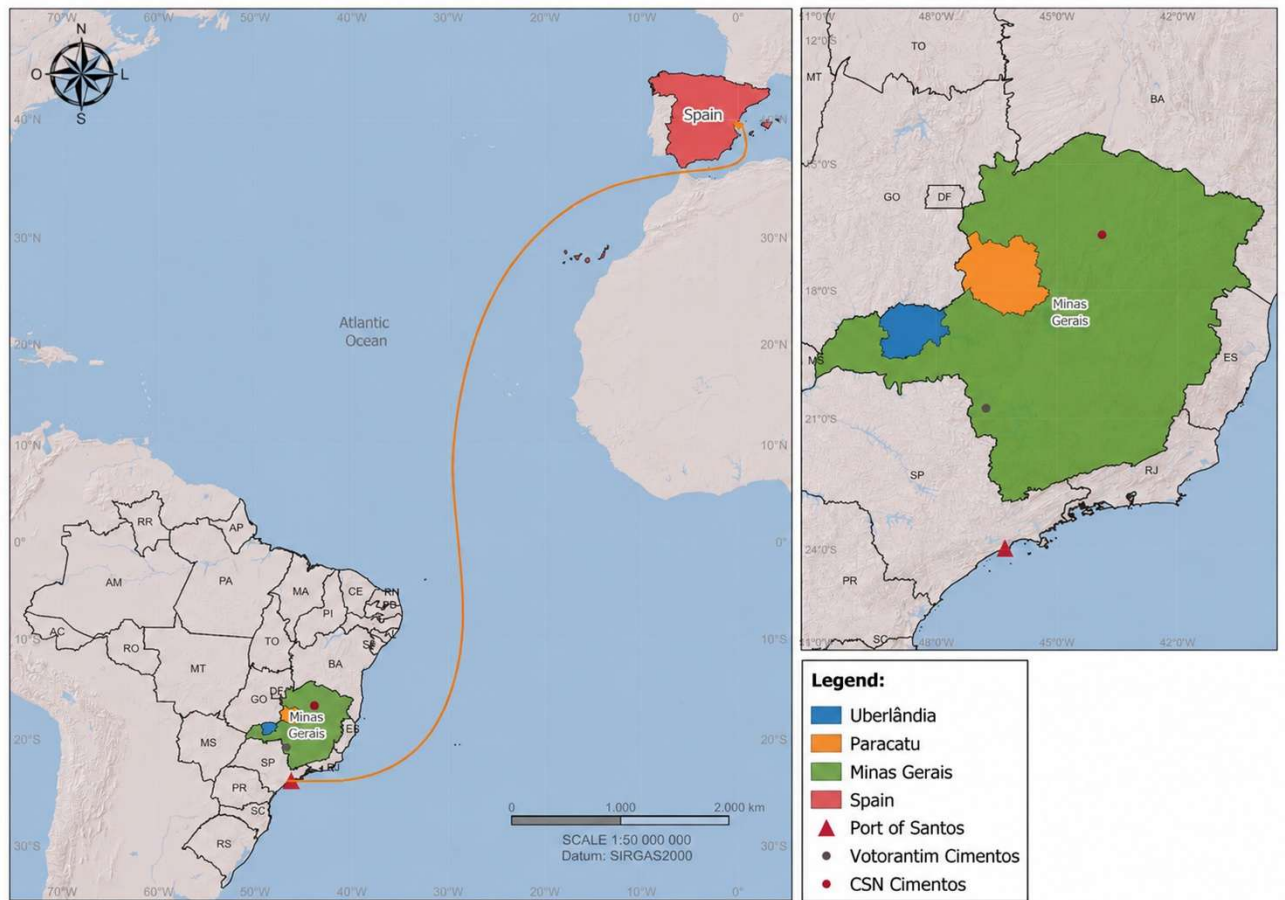


Figure 13 - Spatial representation of the electrolysis regions, CO₂ sources, the Port of Santos, and the export route to Spain used in the assessed scenarios.

In Scenario 1, hydrogen produced via electrolysis is transported in compressed form to the nearest cement plant along each route, where it is combined with CO₂ captured from cement industries in Minas Gerais for methanol synthesis. This integration of hydrogen production and CO₂ capture creates a carbon utilization pathway in which industrial emissions are incorporated into the production of methanol. As previously mentioned, this pathway was selected due to methanol's potential as an alternative fuel for internal combustion engines, as well as its favorable storage and transport characteristics compared to gaseous hydrogen. CO₂ from cement plants was used because Minas Gerais has a high concentration of cement industries, resulting in elevated emission levels and making the region suitable for carbon capture and utilization (Meijssen; Becattini; Mazzotti, 2024; Oliveira, 2019). After synthesis, the methanol is transported to the Port of Santos, which was selected due to its proximity to Minas Gerais and its strategic role as Brazil's largest export port, providing extensive maritime connections and well-established road and rail infrastructure for international cargo transport. The methanol is subsequently exported to Spain.

In Scenarios 2 and 3, hydrogen is compressed or liquefied for subsequent export, respectively. These pathways were chosen because they are currently among the main technological options for long-

distance hydrogen transport (IRENA, 2022b). In Scenario 2, hydrogen is compressed and stored in high-pressure tanks at 350 bar. In Scenario 3 hydrogen is cryogenically liquefied before maritime transport. Upon arrival in Spain, liquefied hydrogen is vaporized through boil-off during storage and handling, and then compressed to the pressure required for end use.

In Scenario 4, hydrogen is converted into green ammonia via the Haber-Bosch process. In this process, hydrogen produced by electrolysis reacts with nitrogen separated from the atmosphere under high temperature (typically 400–500 °C) and high pressure (150–300 bar), using an iron-based catalyst to produce ammonia (NH₃). As also discussed in the Introduction, ammonia is widely regarded as a promising hydrogen carrier because of its high volumetric energy density and the availability of well-established storage and transportation infrastructure (IRENA, 2022b).

In Spain, the fuels are then used in stationary internal combustion engines for electricity generation. In addition to conventional diesel, hydrotreated vegetable oil (HVO) was considered as a pilot fuel because it is a commercially available renewable fuel already deployed in Europe and represents a promising option for reducing the environmental impacts associated with dual-fuel engine operation. Evaluating HVO also makes it possible to assess whether hydrogen carriers can provide additional environmental benefits when combined with an already sustainable alternative to diesel. The hydrogen and methanol pathways were therefore evaluated in dual-fuel configurations using both diesel and HVO, while the ammonia pathway was assessed in a dual-fuel configuration with diesel. The energy substitution rates adopted for each configuration are presented in Section 2.2.9.

The LCA considered the following impact categories:

1. Global Warming Potential (GWP),
2. Fossil Resource Scarcity (FRS),
3. Fine Particulate Matter Formation (FPMF),
4. Ozone Formation (OF), including Human Health and Terrestrial Ecosystems,
5. Human Toxicity (HT), including carcinogenic and non-carcinogenic, and
6. Environmental Toxicity (ET), including terrestrial, freshwater, and marine ecotoxicity.

The GWP category was selected to evaluate GHG emissions associated with fuel production, transportation and use. FRS was included to assess fossil resource consumption across the different scenarios. FPMF and OF were considered because of the relevance of particulate matter, NO_x, CO, and hydrocarbon emissions from combustion processes, which can directly affect air quality. Finally, the HT and ET categories were included to evaluate the potential impacts of emissions and production processes on human health and on terrestrial and aquatic ecosystems.

Inventory

Hydrogen Production – Electrolysis

Alkaline electrolysis (AEL) is the hydrogen production pathway considered in this study. AEL was selected since it is a highly technologically mature and widely applied industrial process (Sadeghi; Ghandehariun; Rosen, 2020; Zhang et al., 2022). Data on electrolyzer manufacturing and operation were obtained from (Koj et al., 2017). The system was modeled with a service life of 20 years, and annual operating time of 8300 hours, assuming a hydrogen production rate of 118 kg H₂/h at 33 bar. Electricity consumption for the electrolysis process was assumed to be 50 kWh/kg H₂, with an additional 0.97 kWh/kg H₂ required for compression up to 200 bar (Koj et al., 2017; NREL, 2018).

The oxygen (O₂) generated as a co-product was released into the atmosphere. A linear increase of 5% in electricity demand across the system lifetime was assumed to account for electrolyzer performance degradation over time (Roeder et al., 2024). A stack lifetime of 80000 hours or 10 years of operation was considered (Iyer et al., 2024; Şahin, 2024).

An on-grid configuration was adopted, in which the electrolyzer remained connected to the Brazilian electricity grid. Renewable electricity was sourced using Power Purchase Agreements (PPAs) from dedicated PV or wind power plants (Azevedo, 2023). Under this configuration, the amount of renewable electricity supplied to the grid was equal to the daily electricity demand of the AEL system, even when the temporal profile of renewable generation did not fully coincide with the electrolyzer's operating schedule.

To achieve this, the PV and wind power systems were oversized to ensure that the electrolyzer's daily energy demand was fully provided by renewable generation. Although the system may occasionally draw electricity directly from the transmission grid, the overall energy balance remains entirely linked to renewable sources. This modeling approach is also consistent with the current Brazilian renewable hydrogen certification framework, where green H₂ is classified based on renewable energy contracts, rather than on the direct physical supply of electricity to the electrolyzer (Azevedo, 2023).

The Life Cycle Inventory (LCI) for PV electricity generation was based on (Frischknecht et al., 2015), including module manufacturing and transportation from China to Brazil. The installed PV capacity required to meet the energy demand of the AEL system was calculated according to the methodology proposed by (Müller et al., 2021), using Equations (1) and (2):

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

$$P_{PV} = \frac{A}{PR \times I} \quad (2)$$

Where:

- $AEL_{\text{electricity demand}}$ = electricity needed to power the electrolyzer systems, given in MWh/year;
- A = total area of the PV power system in m²;
- DR = annual degradation rate of 1% (Palmer et al., 2021);
- I = irradiation in *Paracatu* at 5.67 kWh/m²/day (Goulart et al., 2026);

- P_{PV} = power capacity of the PV system, given in MWp;
- PR = performance ratio of 78% (Palmer et al., 2021);
- T = PV system's lifespan, set at 30 years; and
- η = module efficiency of 17.5% (Frischknecht et al., 2015).

The LCI for wind power generation was based on (Arvesen; Hertwich, 2012), including data on manufacturing and transporting the turbine, rotor, and nacelle from Denmark to Brazil (Fonseca; Carvalho, 2022; Gomaa et al., 2019). The installed wind capacity required for the system was estimated using Equation (3):

$$P_{Wind} = \frac{AEL_{electricity\ demand}}{CF \times T} \quad (3)$$

Where:

- $AEL_{electricity\ demand}$ = electricity needed to power the electrolyzer systems, given in MWh/year;
- CF = capacity factor of 47%, i.e., estimated wind energy potential in *Uberlândia* (Minas Gerais, Brazil) (Goulart et al., 2026) and
- T = the wind system lifespan, set at 20 years (Arvesen; Hertwich, 2012).

The LCI for biomass-based electricity generation was based on the ecoinvent database (Ecoinvent, 2019) and represents a state-of-the-art combined heat and power (CHP) plant fueled with wood chips, with an installed capacity of 6.67 MW.

HVO Production

For HVO production, the inventory for used cooking oil (UCO) collection and processing was based on (Capaz, 2021). UCO is one of the main feedstocks used in the production of renewable fuels and accounts for approximately 24% of the raw material mix used in biodiesel and HVO production in Europe (European Biodiesel Board, 2024). From a LCA perspective, UCO is treated as a waste product; therefore, the environmental burdens associated with the cultivation of oil crops and the production of the original vegetable oil are not allocated to it.

Data describing the HVO production process were obtained from (Pearlson; Wollersheim; Hileman, 2013). The inventory assumes that the hydrogen consumed during the hydrotreatment stage is derived from fossil sources, reflecting current industrial practice and contributing to the environmental impacts associated with HVO production. Since the HVO production process generates multiple co-products, including Sustainable Aviation Fuel (SAF), naphtha, and light streams, environmental burdens were allocated among the products based on their mass.

Diesel Production

For diesel production, the European diesel market dataset available in the Ecoinvent database (Ecoinvent, 2019) was used. This dataset represents the supply and distribution of diesel to the final consumer, including transportation from the refinery to the end user, operation of storage facilities and fuel stations, and the associated emissions from fuel evaporation and wastewater treatment.

Methanol Production

For methanol production, the inventory from (Rossi et al., 2020) was used for compressed hydrogen storage in a 350-bar Type III tank, a common technology for high-pressure hydrogen storage, followed by transportation to the methanol synthesis unit. Data related to CO₂ capture from cement plants were obtained from (Dahiru, 2026), while the methanol synthesis stage was modeled using data from the (European Commission, 2024).

Hydrogen Compression

For hydrogen compression, the inventory from (Rossi et al., 2020) was used for a Type III storage tank operating at 350 bar. The hydrogen storage capacity was estimated using the volumetric density of H₂ at 350 bar and 0 °C, corresponding to 25 kg/m³ (PNNL, [S.d.]). Considering a tank volume of 258 L (0.258 m³), the storage capacity was calculated as 6.45 kg H₂. Electricity consumption for compression to 350 bar, corresponding to 1.38 kWh/kg H₂, was obtained from (Khan et al., 2021).

Hydrogen Liquefaction

For hydrogen liquefaction, the inventory from the (European Commission, 2024) was adopted, while the electricity requirement of 12 kWh/kg H₂ was based on (Wei et al., 2025).

After transportation and storage, liquid hydrogen is converted back to its gaseous phase via the boil-off process, which occurs naturally via heat absorption when exposed to the surrounding environment. Since the resulting gaseous hydrogen is initially at approximately 1 bar, an additional compression step was included to raise the pressure to 5 bar, which is the hydrogen inlet pressure required for supplying the internal combustion engine. For this stage, an electricity consumption of 0.79 kWh/kg H₂ was assumed (Khan et al., 2021).

Ammonia Production

For ammonia production processes, the inventories provided by the (European Commission, 2024) were adopted.

Transportation

Road transportation from the producing microregions to the Port of Santos was modeled using Euro IV trucks. For the compressed hydrogen, liquefied hydrogen, and ammonia pathways, hydrogen production was modeled in *Paracatu* for the PV electrolysis route and in *Uberlândia* for the wind- and biomass-based electrolysis routes. Road transport distances from *Paracatu* and *Uberlândia* to the Port of Santos were 930 km and 700 km, respectively.

Compressed hydrogen produced via electrolysis is delivered in a Type III tank to the nearest cement plant for each route, where methanol is produced via synthesis. The CO₂ used in the process was assumed to be captured from cement plants in Minas Gerais, given the high concentration of plants in the state. *CSN Cimentos*, located in *Montes Claros*, approximately 466 km from *Paracatu*, was selected

for the PV route. *Votorantim Cimentos*, located in *Itaú de Minas*, approximately 337 km from *Uberlândia*, was selected for the wind and biomass routes.

After production, methanol is then transported from these cement plants to the Port of Santos. The distance from *CSN Cimentos* to the Port of Santos is approximately 1080 km, while the distance from *Votorantim Cimentos* to the port is approximately 450 km. The fuel is then exported over approximately 9000 km by sea to Spain.

Electricity Generation (Internal Combustion Engine – ICE)

Since emission data for compression-ignition (CI) engines operating in dual-fuel mode with hydrogen carriers under real-world conditions remain limited, particularly when optimized engine settings are applied instead of default configurations for conventional diesel-only operation, the inventory data for the use phase were derived from experimental tests. These tests were conducted on a single cylinder compression-ignition engine (SCE) operating in dual-fuel mode at two load conditions, 25% and 75% of the maximum load at 1600 rpm. These two load conditions allow for a more realistic assessment of the performance of H₂-derived fuels under varying energy demand scenarios. Indeed, all the fuels tested have been shown to perform worse at low loads, where lower in-cylinder temperatures and ultra-lean fuel–air mixtures (together with the significant cooling effect of methanol when used), can lead to increased THC and CO emissions (Domínguez et al., 2023, 2025). In the case of ammonia, only low load was tested due to the significant NH₃ engine-out emission at such high ESR and ammonia consumption rate.

The AVL 580-036 engine used is a four-stroke SCE equipped with a high-pressure common-rail injection system, an AVL RPEMS™ CR electronic control unit, and a water-cooled high-pressure exhaust gas recirculation (EGR) system, without exhaust gas aftertreatment technologies. The engine has a compression ratio of 15.84:1, a cylinder bore of 106.5 mm, and a stroke of 127 mm. Liquid fuels were supplied through direct injection, while H₂-derived fuels were introduced through port fuel injection. Liquid fuel consumption was measured using AVL 433S gravimetric scales, whereas gaseous fuel consumption was monitored using a Bronkhorst® flow meter. Other characteristics of the SCE, as well as those of the emissions measurement devices (which enable the determination of CO₂, NO_x, N₂O, THC, CO, particulate matter, CH₄, as well as unburnt H₂ and NH₃), can be found elsewhere (Domínguez et al., 2023, 2025). The engine is representative of off-road applications as well as medium-duty trucks and buses. For the use-phase modeling, a nominal power output of 160 kW was assumed for the genset, corresponding to widely deployed commercial multi-cylinder units equipped with six cylinders and exhibiting geometrical and performance characteristics very similar to those of the tested SCE. These engines typically comply with EU emission standards for non-road engines up to Stage IIIA (equivalent to US EPA Tier 3). Although Stage IIIA is now considered an outdated regulatory level (no aftertreatments devices are required), a substantial share of gensets currently in operation still falls

within this category, making it a relevant and realistic reference for practical applications and emissions assessments.

An energy substitution ratio (ESR) of 35% was experimentally evaluated, corresponding to 35% of the total energy demand being supplied by the secondary fuel (H_2 , methanol, or ammonia), thereby displacing diesel or HVO. As previously noted, the emissions and fuel consumption data used for the LCA correspond to optimized engine settings (exhaust gas recirculation rate, injection timing and strategy, and injection pressure) under dual-fuel operation with each H_2 carrier. Figure 14 presents the engine used in the experiments.

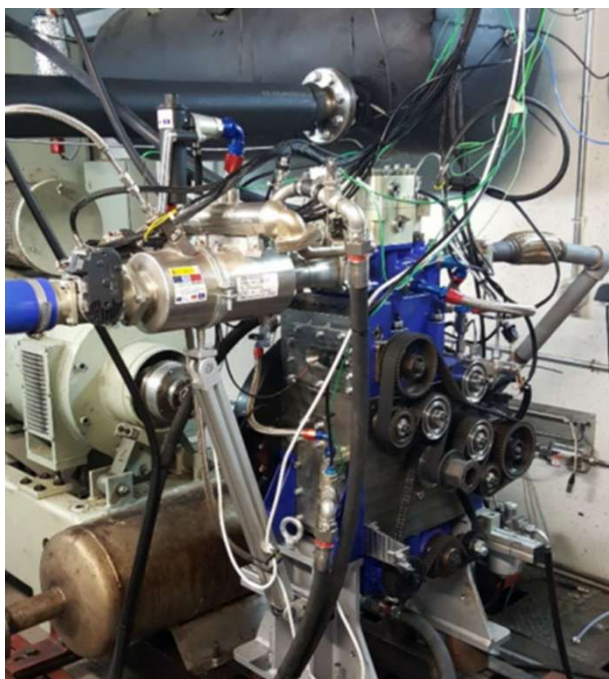


Figure 14 - AVL 580-036 single-cylinder CI engine.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate how changes in the primary fuel energy substitution fraction affected the environmental performance of the system. The reference condition consisted of replacing 35% of the primary fuel energy (diesel or HVO) with gaseous fuel in dual-fuel mode. The replacement of approximately 20% and 60% of the primary fuel energy (diesel or HVO) with gaseous fuel in dual-fuel mode was also experimentally evaluated to assess how different gaseous fuel substitution levels affected system performance during engine operation.

A further sensitivity analysis was also performed to investigate how key assumptions in HVO production affected environmental performance. First, the influence of the hydrogen source was assessed by comparing the baseline scenarios, in which HVO was assumed to be produced using fossil-derived hydrogen in Europe, with equivalent scenarios in which HVO was produced using green hydrogen from Minas Gerais, Brazil, generated through PV-powered water electrolysis. This allowed

the environmental effects of replacing fossil-derived hydrogen with renewable hydrogen to be quantified. Second, the influence of the feedstock was evaluated by replacing UCO with rape oil in the HVO production process, allowing the environmental implications associated with the use of a virgin vegetable oil feedstock instead of a waste-derived feedstock to be assessed.

3.3. Results and discussion

Global Warming and Fossil Resource Scarcity

The GWP results shown in Figure 15 reveal substantial differences among the evaluated scenarios, mainly driven by the type of fuel used and the characteristics of the associated energy supply chains. Overall, diesel-based scenarios showed the highest climate impacts, whereas HVO-based scenarios achieved significant reductions in CO₂-equivalent emissions under both high- and low-load operating conditions.

In Scenario 0, i.e., the reference scenario, where only diesel fuel was employed, the use phase accounted for the largest share of the total impact, contributing approximately 85% of the total GWP. This was primarily because the combustion of fossil carbon leads to net CO₂ emissions into the atmosphere. Additional contributions arose from the fuel production stage, including petroleum extraction, transportation, and refining processes. This result is consistent with the findings reported by (El Hannach et al., 2019). The high environmental impacts associated with diesel are also reflected in the FRS category (Figure 16), where diesel-only scenarios showed the highest values among all evaluated alternatives. While GWP is largely driven by CO₂ emissions generated during combustion, FRS represents the demand for fossil resources throughout the fuel production chain.

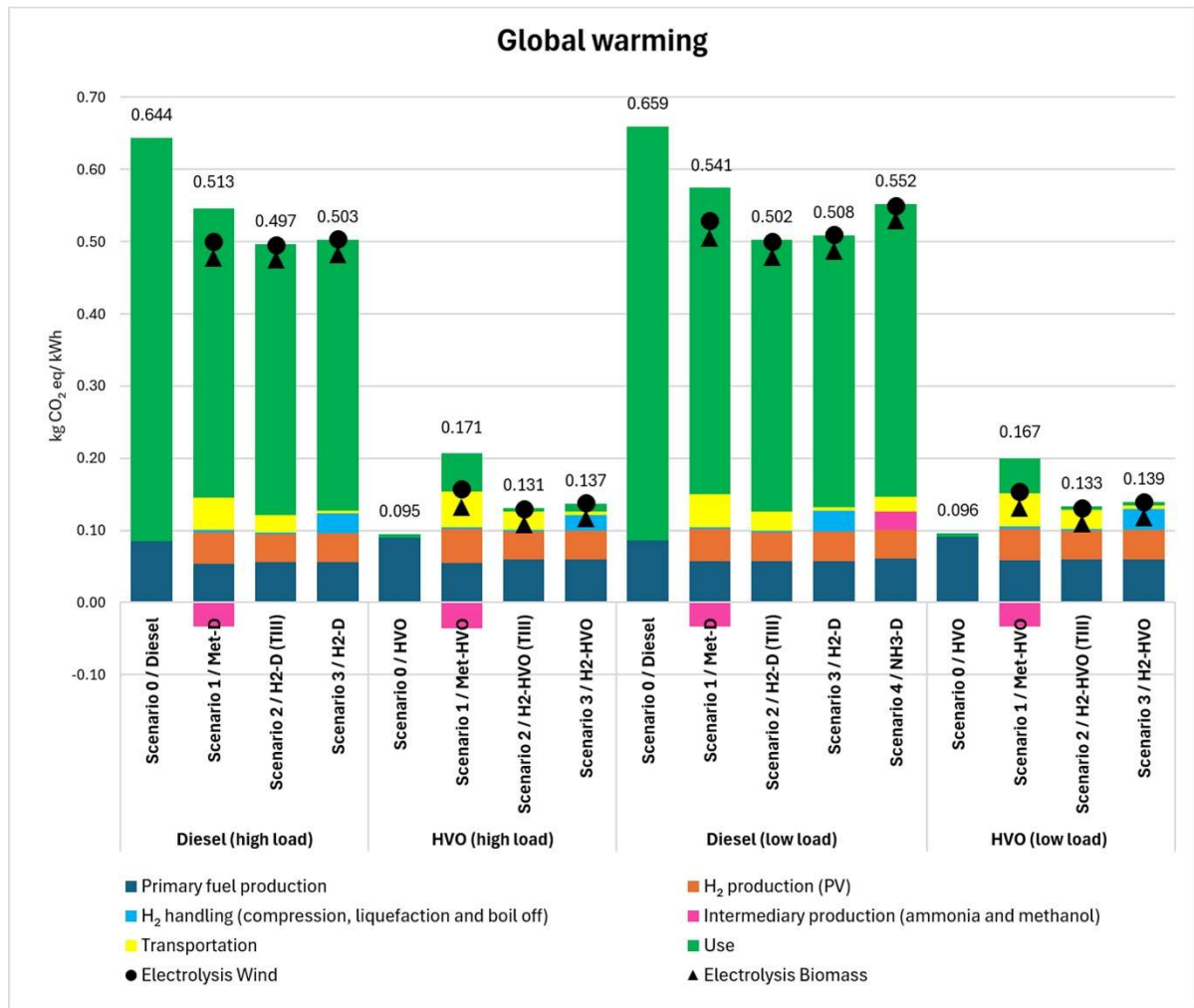


Figure 15 - Global warming potential (GWP) for the evaluated scenarios.

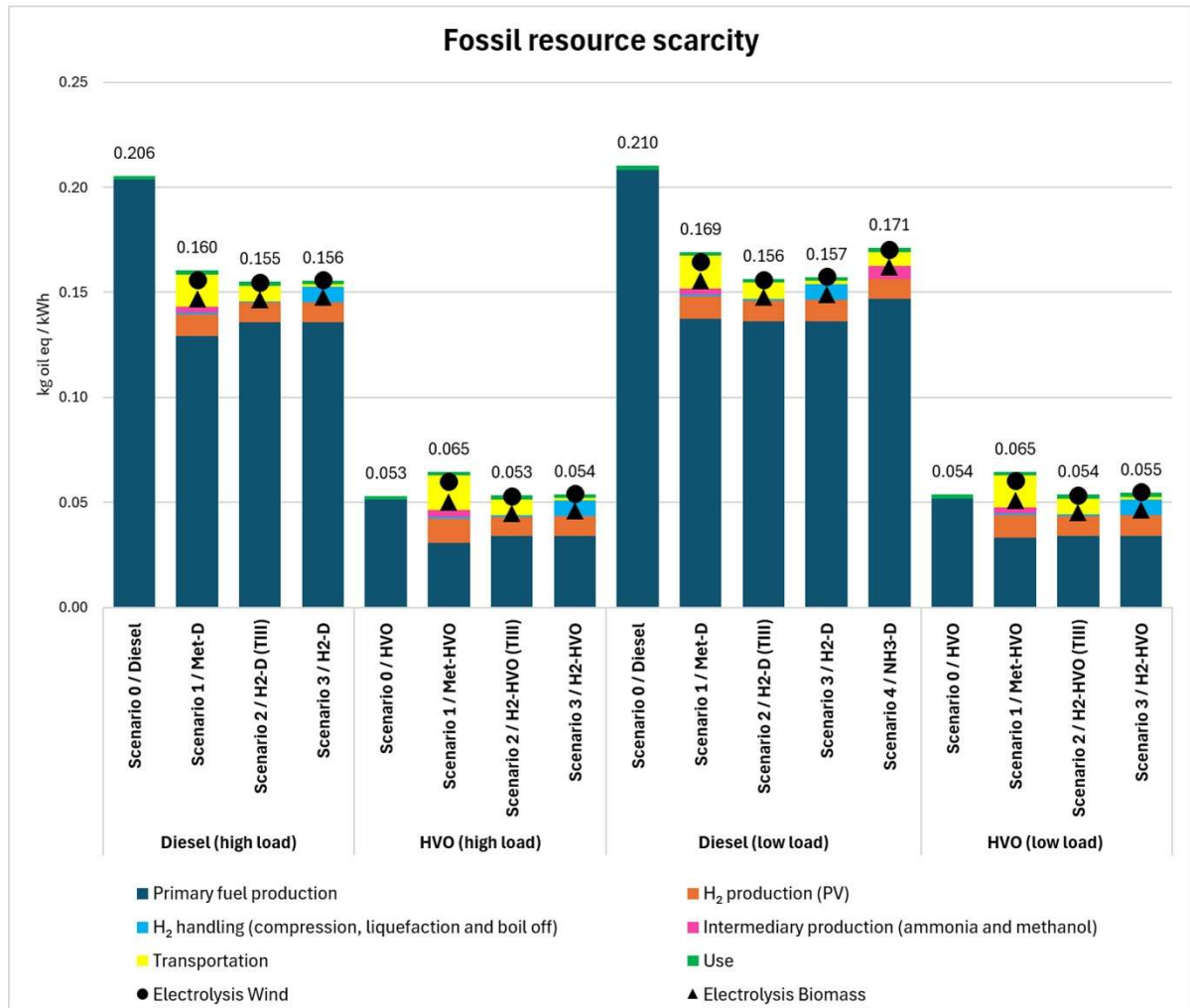


Figure 16 - Fossil resource scarcity potential for the evaluated scenarios.

Introducing hydrogen into dual-fuel operation resulted in significant reductions in GWP, ranging from 16% to 24% relative to conventional diesel operation. In Scenarios 2 and 3 (Diesel–H₂), lower climate impacts were observed under both load conditions due to partially replacing fossil fuel with a carbon-free energy carrier during combustion. This result is consistent with the findings reported by (Akhtar et al., 2025; Dimitriou et al., 2018; Pinto et al., 2023a), who showed that the use of hydrogen in dual-fuel engines reduces diesel consumption and combustion-related carbon emissions. However, the FRS results indicate that these scenarios continue to rely heavily on fossil resources, since diesel still serves as the pilot fuel. Consequently, although GHG emissions are reduced, the decrease in fossil resource demand is less pronounced, suggesting that climate benefits are not necessarily accompanied by proportional reductions in dependence on petroleum-based fuels.

In hydrogen-based scenarios, the H₂ production and conditioning stages also contribute to total GWP. Although the GWP associated with these stages remains lower than that of the engine operation, their relative contribution increases as the impacts of the primary fuel decrease. Figure 15 shows that the GWP associated with hydrogen production, together with the compression, liquefaction, and boil-

off processes, accounts for approximately 7% to 50% of the total impact, depending on the scenario evaluated. Similarly, the GWP associated with the H₂ supply chain is of the same order of magnitude as that associated with primary fuel production, even though hydrogen accounts for only a fraction of the total energy supplied in dual-fuel configurations. This suggests that part of the environmental benefits associated with reducing diesel consumption may be offset by impacts arising from green hydrogen production and supply, making overall system performance strongly dependent on the selected production pathway. This finding is consistent with previous LCA studies that identified hydrogen production as a critical stage in low-carbon energy systems (Ajeeb et al., 2025; Gomes, 2023).

The results reveal important differences among the hydrogen production pathways evaluated. As shown in Figures 15 and 16, hydrogen produced via electrolysis powered by biomass-based electricity exhibited the lowest GWP and FRS impacts among all analyzed routes, followed by wind-powered electrolysis and PV solar-powered electrolysis. These differences reflect the influence of the electricity source used in the electrolysis process, which has been widely recognized as one of the main factors determining the environmental performance of green hydrogen production (Maciel et al., 2023; Silva; Capaz, 2025).

Among the evaluated pathways, the biomass-based route showed the lowest climate impacts, reducing GWP by 4% to 23% compared with the PV route. This is because renewable feedstocks containing biogenic carbon are used, which contribute to lower net GHG emissions over the life cycle. Wind-powered electrolysis showed GWP values up to 8% lower than those of the PV pathway, mainly due to the higher lifetime electricity generation and lower material requirements per unit of electricity produced. By contrast, PV systems showed additional impacts associated with module and component manufacturing. These findings are consistent with recent studies highlighting electricity source selection as a key factor in reducing the environmental impacts of hydrogen production via electrolysis (Ajeeb; Costa Neto; Baptista, 2024; Cho; Strezov; Evans, 2023).

In scenarios involving methanol and ammonia, distinct patterns contributing to GWP impacts emerged. For methanol scenarios, the synthesis stage contributed negatively to GWP because CO₂ captured from cement plants was used as a feedstock. However, this benefit is insufficient to offset the high impacts associated with the use phase. This remains the main contributor to total GWP in these scenarios. This can be explained by the fact that the carbon incorporated into methanol during production is released again during combustion, effectively offsetting the benefits of carbon capture under the modeling assumptions adopted in this study. According to (Domínguez et al., 2023), partially replacing diesel with methanol in dual-fuel engines reduces fossil fuel consumption and can lower direct CO₂ emissions, since methanol has a lower carbon-to-hydrogen ratio. However, since methanol is still a carbon-based fuel, CO₂ is still released when it is burned. Previous LCA studies have also identified the use phase as a major contributor to GWP in methanol-based systems (Accardo et al., 2024; Amat Ventayol et al., 2025). The FRS results support this, since methanol scenarios show lower impacts than

diesel-based systems but higher impacts than HVO-based alternatives. This suggests that, although GHG emissions can be reduced, dependence on fossil resources throughout the supply chain is not entirely eliminated.

The spatial configuration of the methanol supply chain may also partly explain the impacts observed. Unlike the other pathways, methanol production requires an additional logistical stage in which hydrogen is first transported to cement plants for fuel synthesis. The produced methanol is then transported to the port for export. This additional transport step increases both energy consumption and associated emissions. As a result, transportation contributes between 8.5% and 28.7% of total GWP in methanol-based scenarios. For compressed hydrogen, liquefied hydrogen, and ammonia pathways, this contribution ranges from 0.8% to 19.2% of total GWP. These findings show that transportation logistics limit the environmental performance of the methanol pathway.

By contrast, the NH₃-D scenario showed higher GWP and FRS impacts than the methanol scenario. This is because environmental impacts accumulate across the entire ammonia supply chain, i.e., from synthesis to final use in the engine. Although ammonia does not contain carbon, it is produced via energy-intensive processes, particularly synthesis through the Haber-Bosch process, where, in this study, energy consumption is on the order of 0.81 kWh kg⁻¹ of NH₃ produced. Furthermore, significant amounts of nitrous oxide (N₂O), a GHG with a high GWP, are produced when ammonia is burned in dual-fuel engines. The greater warming intensity of N₂O contributes to GWP of a similar magnitude, corresponding to approximately 374 g CO₂-eq kWh⁻¹, even though N₂O emissions are much lower than CO₂ emissions (1.37 g kWh⁻¹ compared with 400.18 g kWh⁻¹). A similar effect was reported by (Domínguez et al., 2025).

Overall, the most favorable results among the hydrogen-based alternatives were observed for compressed hydrogen scenarios, which showed lower impacts than the liquefied hydrogen, methanol, and ammonia pathways. This is because additional steps that increase energy consumption and emissions throughout the fuel supply chain are absent, e.g., the liquefaction and boil-off processes. These processes also contribute to higher indirect resource demand across the life cycle, explaining why environmental performance for compressed hydrogen improved relative to pathways that require additional processing steps.

The HVO-based scenarios were the most environmentally favorable scenarios of all evaluated alternatives. GWP for HVO was approximately 85% less under both load conditions, compared to conventional diesel. This highlights the strong potential of HVO for mitigating GHG emissions. This was also reflected in the FRS category, where GWP was approximately 74% less, indicating that replacing diesel with HVO can simultaneously support energy system decarbonization and reduce dependence on fossil resources. This is because HVO produced from used UCO is renewable, and has zero biogenic carbon emissions within this impact category. From a methodological perspective, UCO is treated as a waste product, meaning that the environmental impacts associated with producing the

original vegetable oil are not allocated to it. Rather, only collection, transportation, and processing impacts are considered. As a result, HVO has a substantially lower carbon intensity than fossil diesel. In our study, HVO production resulted in a carbon footprint of 0.521 kg CO₂-eq kg⁻¹ of HVO, highlighting its potential to reduce GHG emissions when using residual feedstocks.

Xu et al. (2022) reported that renewable diesel produced from UCO can reduce GHG emissions by approximately 79–86% compared with petroleum-derived diesel, with significantly lower life-cycle emissions than conventional production pathways. Similarly, (Ajeeb et al., 2025) found that HVO production using UCO and green hydrogen results in GWP ranging from 0.304 to 0.748 kg CO₂-eq kg⁻¹ of HVO. The lowest values were observed when renewable electricity sources were employed. (Roque et al., 2023) also highlighted that hydrotreated fuels derived from residual feedstocks show better environmental performance than fossil fuels and pathways based on virgin vegetable oils, further reinforcing the potential of UCO as a feedstock for sector decarbonization.

Additionally, (Hosseinzadeh-Bandbafha et al., 2022; Ou et al., 2022) emphasize that waste-based pathways offer significant advantages in resource-use categories because they avoid virgin fossil feedstock extraction. Furthermore, scenarios that considered hydrogen, methanol, and ammonia blended with HVO also showed FRS values that were very close to FRS values for pure HVO. This may be because the hydrogen used in the hydrotreatment stage of HVO production is derived from fossil sources, introducing a non-renewable component into the fuel production chain, making the evaluated scenarios more similar in FRS outcomes.

The combined analysis of GWP and FRS indicators indicates that scenarios with better climate performance also tend to show lower dependence on fossil resources, particularly in the case of HVO produced from waste feedstocks. By contrast, hydrogen-derived synthetic fuels suggest that reductions in GHG emissions are not necessarily accompanied by proportional decreases in fossil resource scarcity.

Air Quality-Related Impacts

The FPMF and OF impact categories represent potential effects on air quality resulting from atmospheric emissions throughout the fuel life cycle. FPMF is associated with the direct emission of particles and their precursors, whereas tropospheric OF mainly results from emissions of nitrogen oxides and volatile organic compounds involved in photochemical reactions in the atmosphere (European Commission, 2024).

Figure 17 presents the results for FPMF across the evaluated scenarios. The results show that the use phase contributes the most, accounting for between 14% and 91% of the total impact. Scenario 4 (NH₃-D) showed the highest impact potential, with 5.984 g PM_{2.5}-eq kWh⁻¹, which is about thirteen times higher than the reference diesel scenario (0.460 g PM_{2.5}-eq kWh⁻¹), and nearly thirty times greater than the lowest-impact scenario (HVO–H₂ at low load, 0.210 g PM_{2.5}-eq kWh⁻¹).

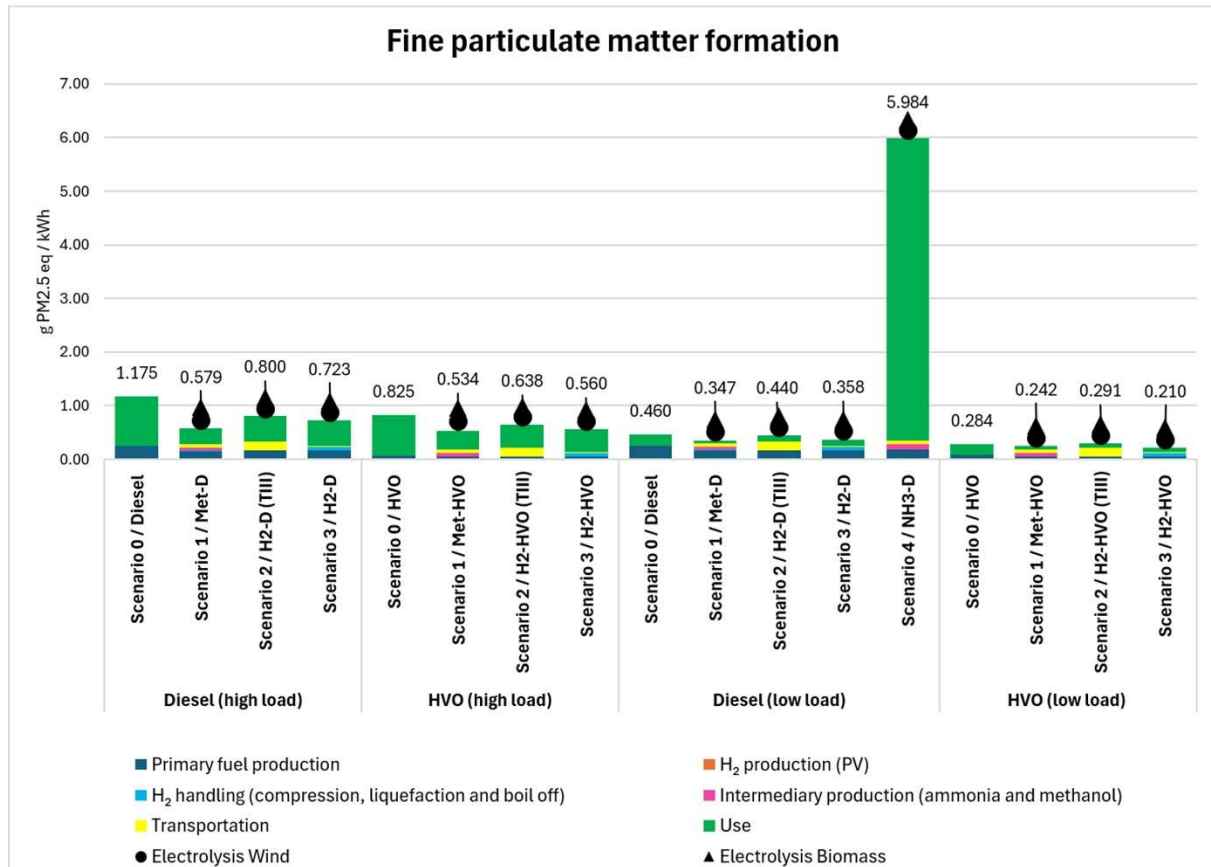


Figure 17 - Fine particulate matter formation potential for the evaluated scenarios.

Analysis indicates that more than 90% of the total impact observed in the NH₃-D scenario comes from the fuel use stage. This suggests that emissions from burning ammonia are the primary contributor to environmental hotspots in this category. Although ammonia is a carbon-free fuel and does not produce soot-related particulate matter, these results can be attributed to two different effects. First, since the SCE was operated under optimized conditions for each fuel combination, dual-fuel operation with ammonia required a reduction in diesel injection pressure (Domínguez et al., 2025) to enhance ammonia combustion efficiency. This, in turn, led to higher particulate emissions compared to conventional diesel operation. Increasing the ESR with ammonia would probably lead to lower PM emissions compared to conventional single-fuel diesel operation, despite the anticipated rise in unburnt NH₃ emissions.

Although ammonia combustion generally suppresses primary soot formation because it is a carbon-free fuel, the NH₃-D scenario exhibited the highest impact in the particulate matter formation category. This result is mainly explained by the specific operating conditions adopted in this study, namely a relatively low ammonia energy share (35%) under low-load operation with optimized engine settings that required reduced diesel injection pressure. Under these conditions, the reduction in primary particulate emissions was not sufficient to offset the increased formation of gaseous nitrogen-containing species. In particular, ammonia combustion releases unreacted ammonia (ammonia slip) and nitrogen oxides (NO_x), which are important precursors of secondary particulate matter formation (Wu et al.,

2024). Atmospheric reactions between ammonia and acidic compounds produce ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$), both major constituents of $\text{PM}_{2.5}$ (Alnajideen et al., 2024). Consequently, despite its low soot-forming tendency, ammonia can exhibit a high particulate matter formation potential in a LCA when secondary aerosol formation is considered. It should also be noted that increasing ammonia substitution ratios have been shown to reduce particulate emissions due to the carbon-free nature of ammonia, which may improve the overall particulate matter performance of ammonia dual-fuel operation (Domínguez et al., 2025).

The HVO- and hydrogen-based scenarios showed the lowest FPMF impacts. Partially replacing diesel for hydrogen leads to lower combustion-related emissions. The lack of carbon in the H_2 molecule eliminates soot formation and reduces the emission of primary particles (Tsujimura; Suzuki, 2017). Additionally, HVO contains predominantly paraffinic hydrocarbons, contains no aromatic compounds, and has a high cetane number. These properties promote cleaner combustion and lower particulate matter formation compared with fossil diesel (Dimitriadis et al., 2020). Of all evaluated scenarios, the HVO– H_2 configuration, under low-load conditions, showed the best performance, i.e., impacts of only $0.210 \text{ g PM}_{2.5}\text{-eq kWh}^{-1}$.

Figure 18 shows the OF category results across the evaluated scenarios. In our study, OF was defined as the combined contribution to OF for Human Health and Terrestrial Ecosystems, allowing us to evaluate the potential impacts associated with tropospheric OF in an integrated manner. For the high-load scenarios, the conventional diesel scenario had the highest impact ($17.32 \text{ g NO}_x\text{-eq kWh}^{-1}$), while the Met-D scenario had the lowest impact ($6.18 \text{ g NO}_x\text{-eq kWh}^{-1}$), i.e., a reduction of approximately 64% compared to diesel. Impacts for HVO-based scenarios under high-load conditions ranged from 6.92 to $13.61 \text{ g NO}_x\text{-eq kWh}^{-1}$, depending on the hydrogen production pathway adopted. Under low-load conditions, conventional diesel again showed the highest impact ($4.23 \text{ g NO}_x\text{-eq kWh}^{-1}$), while the H_2 –HVO scenario showed the lowest impact ($1.52 \text{ g NO}_x\text{-eq kWh}^{-1}$), corresponding to a reduction of more than 60% in the OF impact ($\text{g NO}_x\text{-eq kWh}^{-1}$) relative to the diesel scenario. Overall, the results suggest that partially replacing diesel with hydrogen and HVO-derived synthetic fuels can substantially reduce the potential for tropospheric ozone formation.

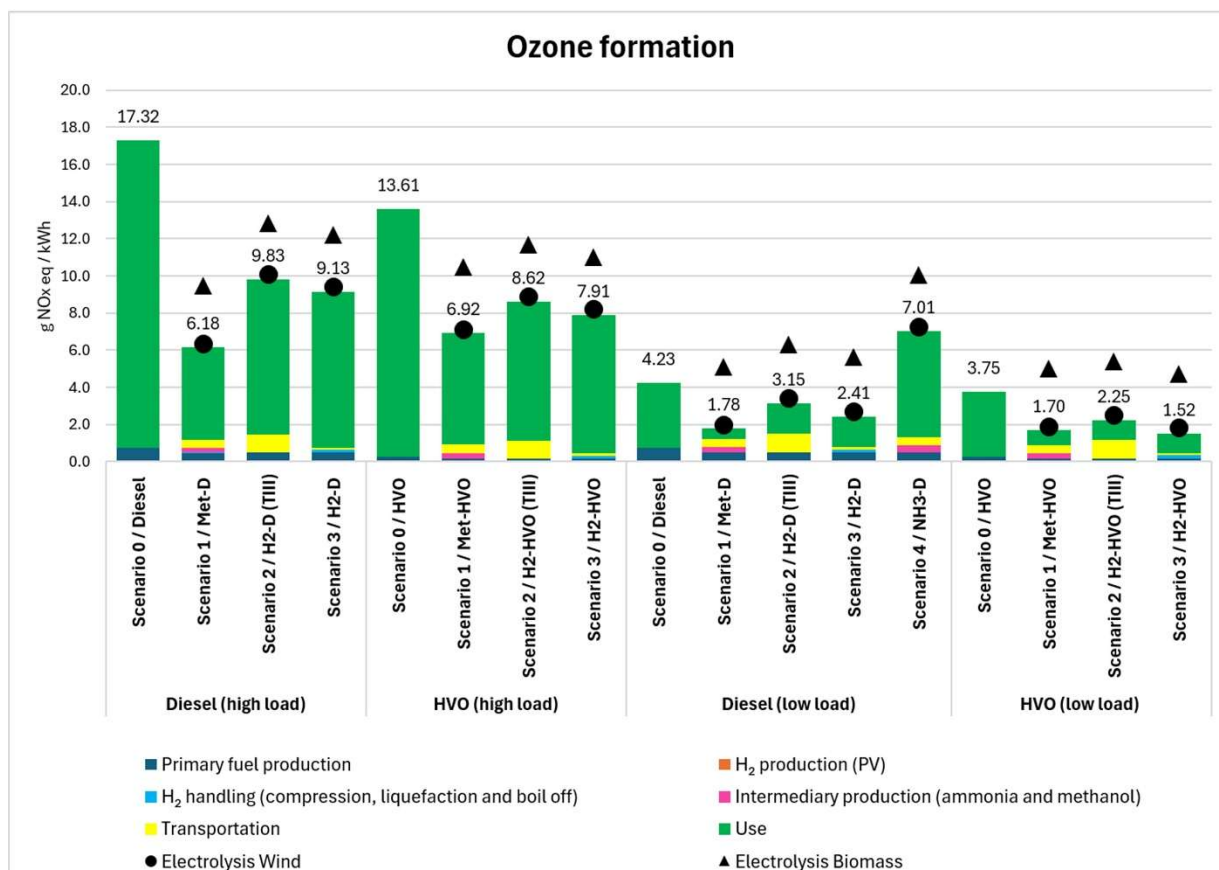


Figure 18 - Ozone formation potential for the evaluated scenarios.

The results followed a pattern similar to that observed for the FPMF category. Scenarios combining HVO and hydrogen exhibited the lowest impacts, whereas the diesel-only scenarios showed the highest impacts. Although the NH₃-D scenario did not exhibit impacts as pronounced as those observed for Fine Particulate Matter Formation, it was also among the scenarios with the highest impacts in the OF category. This result suggests that, although both impact categories are influenced by nitrogen-related emissions, they are governed by different atmospheric processes. While PM_{2.5} formation is closely associated with unreacted ammonia emissions and secondary particle generation, OF is more strongly driven by NO_x emissions produced during ammonia combustion.

Comparisons between the various hydrogen production pathways also highlight how the electricity source used in electrolysis impacts the related air quality category. In both categories, PV-powered electrolysis showed the lowest impacts, followed by wind-powered electrolysis. The similarity between these results suggests that both technologies are environmentally favorable options for hydrogen production. Any observed differences were mainly associated with manufacturing processes and electricity generation infrastructure. By contrast, the biomass-based pathway consistently showed higher impacts. Although biomass is a renewable energy source, there are additional stages in the supply chain, e.g., cultivation, harvesting, processing, transportation, and energy conversion. These additional stages increase NO_x, NH₃, and particulate matter emissions throughout the life cycle (Ajeeb; Costa Neto;

Baptista, 2024; Gomes et al., 2025). These findings show that the environmental benefits associated with hydrogen use depend not only on the fuel employed in the engine, but also on the environmental intensity of its production pathway.

When considering the results on FPMF and OF together, HVO combined with hydrogen produced via PV-powered electrolysis showed the best overall environmental performance among all evaluated scenarios, constituting the most promising alternative for reducing air quality–related impacts.

Toxicity-Related Impacts

The HT and ET categories assess the potential impacts of human and environmental exposure to toxic substances emitted throughout the energy system life cycle. The HT category combines Carcinogenic Toxicity and Non-Carcinogenic Toxicity, allowing an integrated assessment of potential adverse effects on human health resulting from exposure to toxic substances. Similarly, the ET category is the sum of Terrestrial Toxicity, Freshwater Toxicity, and Marine Toxicity, allowing an aggregated evaluation of toxicological effects across different receiving environments, i.e., terrestrial, freshwater, and marine ecosystems. The analysis considered the subcategory with the greatest influence on the aggregated result, which in this case was Terrestrial Toxicity. The total values are the sum of all ecotoxicity categories, while the contribution breakdown reflects the processes that most strongly affect the dominant environmental compartment.

Figures 19 and 20 show the HT and ET results across the evaluated scenarios. For both impact categories, upstream processes are the main contributors to the overall impacts. This contrasts with the air quality–related impact categories, where the use phase was more impactful.

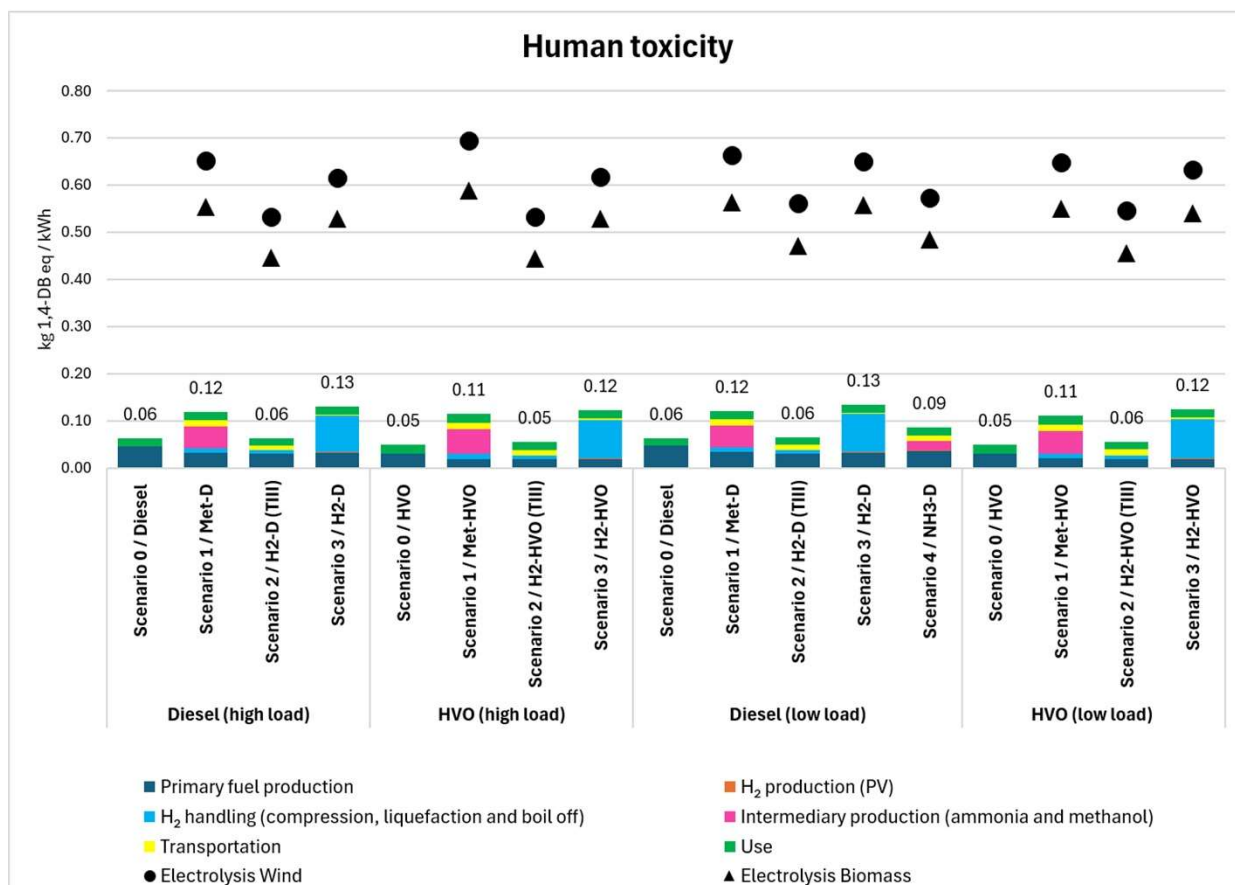


Figure 19 - Human toxicity potential for the evaluated scenarios.

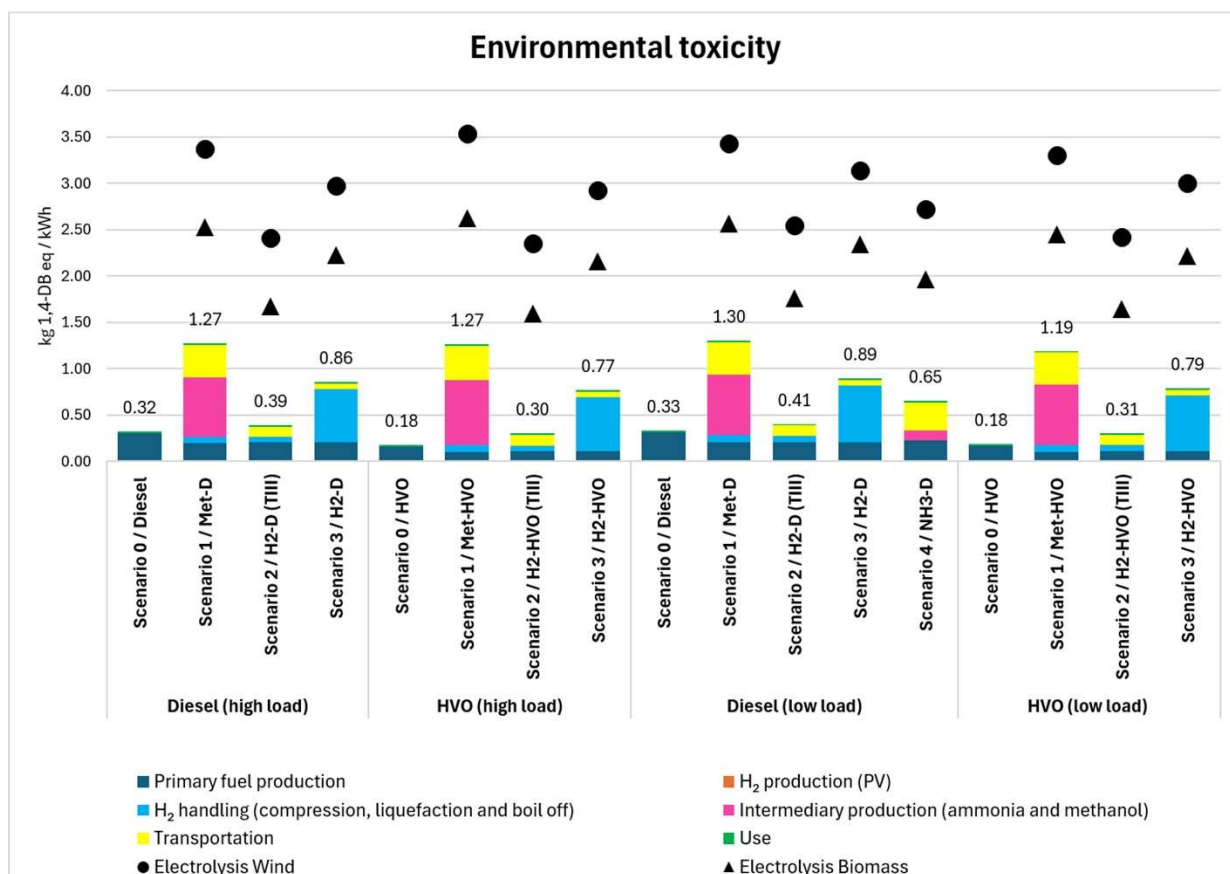


Figure 20 - Environmental toxicity potential for the evaluated scenarios.

Scenarios based exclusively on HVO showed the lowest impacts. The HT result was 0.05 kg 1,4-DB-eq kWh⁻¹, and the ET result was 0.18 kg 1,4-DB-eq kWh⁻¹. These values correspond to reductions of approximately 44% relative to the pure diesel scenario and 86% relative to the Met-D scenario, the latter having the highest environmental toxicity. This suggests that the least technologically complex option of all evaluated pathways is directly using HVO, since there are no additional stages for producing, storing, and conditioning intermediate energy carriers. Additionally, HVO production relies on a relatively mature supply chain and generally depends less on critical materials relative to hydrogen-based pathways and their derivatives. When these materials are extracted and processed, they can cause emissions of potentially toxic substances into the environment, thereby contributing to impacts in both the human and ET categories (Mori et al., 2021).

By contrast, methanol and liquid hydrogen scenarios had the highest toxicological impacts. Contribution analysis shows that these impacts come mainly from the additional stages needed for fuel production, i.e., CO₂ capture and compression, methanol synthesis, and hydrogen liquefaction and transportation processes. These processes increase infrastructure, material, and industrial input demands throughout the production chain, amplifying contributions from upstream material supply systems, e.g., equipment and process inputs. A similar but less pronounced pattern was observed for the NH₃-D

scenario, suggesting that intermediate energy carriers increase production chain complexity, which in turn increases potential toxicological impacts.

The results also indicate that both categories are not greatly impacted by the use phase compared with the other life cycle stages. Primary fuel production, hydrogen handling processes (including compression, liquefaction, and storage), and the intermediate methanol or ammonia production contributed much more across nearly all evaluated scenarios. This is consistent with recent LCA studies that identified equipment manufacturing, electricity consumption, catalyst use, and the infrastructure required for hydrogen production and transportation as the most important sources of toxicological impacts (Ajeeb; Costa Neto; Baptista, 2024; Benavides et al., 2022; Xu et al., 2022).

The hydrogen production pathway also plays an important role in both categories. The results presented in Figures 19 and 20 show that PV-powered electrolysis had the lowest toxicological impacts of all the evaluated alternatives, while wind- and biomass-based pathways had higher values. The higher toxicological impacts associated with wind-powered electrolysis are mainly related to the extraction and processing of metallic materials required for wind turbine manufacturing, including steel, copper, and, in some turbine designs, rare earth elements used in permanent magnets. This interpretation is consistent with the findings of Prasad and Khalid, (2025), who found that hydrogen production using wind-powered electrolysis showed significant contributions to mineral scarcity categories, mainly due to the mining and processing of rare earth elements used in permanent magnets for wind turbines. The authors also reported that sulfide residues generated during copper mining for wind turbine manufacturing contributed to non-carcinogenic toxicity impacts.

The agricultural and logistical characteristics of the supply chain contributed most to the high toxicological impacts in the biomass-based pathway. The cultivation, harvesting, transportation, and energy conversion stages require fertilizers, pesticides, and machinery, and generate soil and atmospheric emissions during biomass processing. LCA studies have shown that biomass-based hydrogen production pathways are particularly sensitive to pesticide, nutrient, and metal emissions to soil and water, which can substantially contribute to toxicity and ecotoxicity categories (Nemecek et al., 2024; Nordborg, 2015; Schweinle, 2015). Therefore, the biomass supply chain may have higher toxicological impacts than the PV pathway, even though biomass is a renewable source, especially when inventories account for agricultural emissions, transportation, and energy conversion processes.

The fact that the environmental impacts for PV-powered electrolysis are largely concentrated in the module and system component manufacturing stages may explain the lower observed toxicity levels for this technology. Once installed, PV systems generate electricity without consuming fuel, without causing direct emissions to soil, water, or air, and operate with relatively low input requirements throughout their lifetime. As a result, potential toxicological impacts are primarily associated with manufacturing processes, particularly semiconductor, glass, aluminum, and other PV module component production. LCA studies indicate that the impacts of these stages tend to be diluted by the

high cumulative electricity generation over the system lifetime, even though they can contribute to the human and ET categories, resulting in lower specific impacts per unit of energy produced (Bhandari; Sekimuli, 2026; IEA PVPC, 2024).

When considering the HT and ET category results together, the main impacts come mainly from the fuel and energy vector production stages, while the use phase contributes relatively little. In this context, HVO shows the best environmental performance, while the addition of hydrogen, methanol, and ammonia increases toxicological impacts due to the greater complexity of their production pathways.

The combined analysis of the evaluated environmental indicators shows that the impacts of different fuels are influenced by both emissions during the use phase and upstream stages throughout their supply chains, highlighting the importance of adopting a life cycle perspective in environmental assessments. The results therefore highlight the importance of gradually replacing fossil diesel with lower-impact alternatives, since diesel shows the highest impacts across most of the evaluated categories. By contrast, HVO-based scenarios showed the best overall environmental performance, with simultaneous reductions in GWP, FRS and toxicological impacts.

The HVO–H₂ combination also shows favorable performance, particularly in air quality–related categories, with the lowest potential for FPMF and tropospheric ozone formation. By contrast, methanol and ammonia scenarios reveal important environmental trade-offs. Although these pathways can reduce fossil fuel dependence and carbon emissions under certain conditions, they also introduce additional impacts associated with fuel synthesis and conditioning processes. Methanol, in particular, had the highest toxicity-related impacts, while ammonia had the greatest FPMF impacts. Additionally, using ammonia in dual-fuel engines without also employing effective emission control systems did not provide climate benefits, since the N₂O emission impacts outweighed the CO₂ emission reductions achieved by partially substituting fossil fuels. These findings indicate that decarbonization strategies focused exclusively on reducing GHG emissions do not necessarily result in the best overall environmental performance, reinforcing the importance of evaluating multiple life cycle impact categories when selecting alternative fuels for internal combustion engines.

Sensitivity Analysis

The results shown in Figure 21 illustrate how variations in key system parameters can influence the estimated environmental impacts. Specifically, the analysis evaluated the effects of changes in the renewable fuel energy substitution rate, as well as the impacts of HVO production using hydrogen generated through PV-powered electrolysis in Minas Gerais compared with fossil-derived hydrogen. This approach allowed us to assess both the robustness of the results and the impact categories most sensitive to the assumptions adopted.

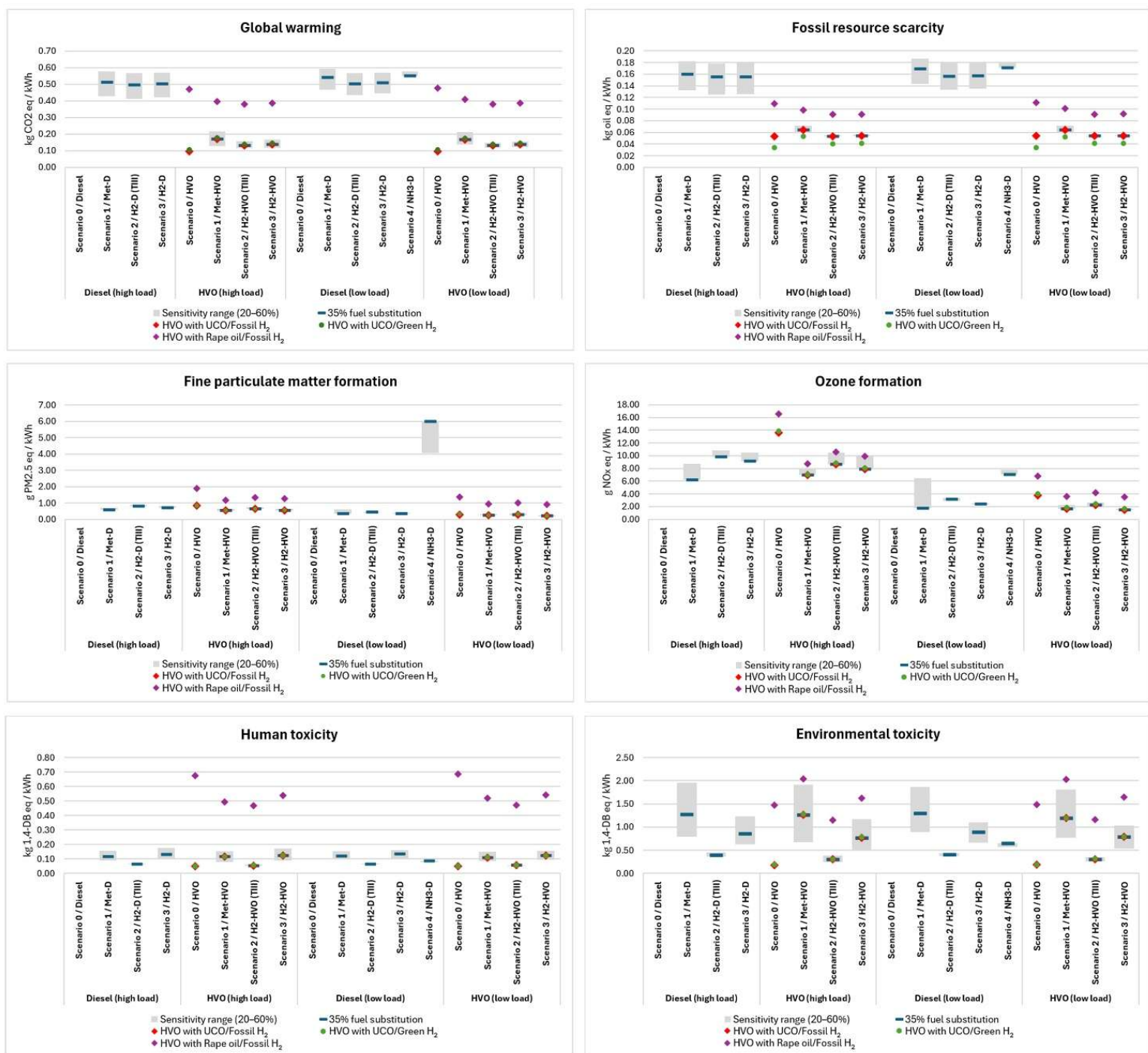


Figure 21 - Sensitivity analysis of LCA results for the studied scenarios, evaluating the influence of fuel substitution rates and HVO production from fossil-based and green hydrogen sources.

Effect of fuel substitution rate (20–60%)

The sensitivity analysis shown in Figure 21 indicates that the renewable fuel substitution rate affects the environmental performance of the evaluated scenarios, although the magnitude of this effect differs across impact categories. The sensitivity bars show that some categories respond more strongly to changes in the share of renewable fuel, whereas others remain relatively stable across the analyzed range (20–60%).

Some variation was observed in the GWP and FRS categories, particularly in diesel-based scenarios. In these cases, increasing the share of renewable fuel led to a more pronounced reduction in both fossil fuel dependence and life cycle–related emissions. By contrast, HVO scenarios showed lower sensitivity to changes in the substitution rate, indicating that a substantial portion of the environmental benefits is already achieved when HVO is used as the primary fuel. This behavior is consistent with LCA studies showing that HVO can reduce GHG emissions and fossil resource demand compared with conventional diesel (Ajeeb et al., 2025; Pinto et al., 2025). Although the lowest impacts in HVO scenarios were observed under the 20% energy substitution condition, the differences among the evaluated rates remained relatively small. In comparison, diesel-based scenarios exhibited a much larger amplitude in the sensitivity results, indicating that outcomes in these categories are more strongly influenced by the share of renewable fuel in the energy mix. This trend is also aligned with the literature on hydrogen and renewable fuels, which shows that reductions in fossil fuel use tend to yield more significant benefits in systems that are originally dependent on mineral diesel (Patel et al., 2024).

For the FPMF and OF categories, the sensitivity analysis showed more distinct variations, with the lowest impacts occurring under the intermediate 35% energy replacement condition in both the HVO- and diesel-based scenarios. The relatively low amplitude of the sensitivity bars indicates that these categories are less influenced by the energy replacement rate and more dependent on fuel properties and combustion mechanisms. This is consistent with the literature, which reports that particulate matter and OF in dual-fuel systems are primarily driven by fuel characteristics and engine operating conditions, making them relatively insensitive to moderate changes in energy substitution rates (Domínguez et al., 2023; Pinto et al., 2023a; Rodríguez-Fernández et al., 2024).

Sensitivity to the energy substitution rate was higher for the HT and ET categories. In both cases, the lowest impacts occurred at the 20% substitution level for both diesel- and HVO-based scenarios. This indicates that toxicological impacts are strongly influenced by processes linked to renewable fuel production and the associated energy supply chains. Unlike atmospheric emission categories, toxicity-related impacts are primarily driven by material demand, infrastructure requirements for fuel production, and the upstream energy used in industrial processes. Recent LCA reviews of hydrogen-based systems show that HT and ecotoxicity are often dominated by production stages and infrastructure materials, particularly in systems based on electrolysis and related equipment (Alves et al., 2025; Molideo, 2020). As a result, increasing the share of renewable fuels does not necessarily lead

to proportional reductions in these categories, since additional production stages can have a stronger influence on the overall environmental inventory.

Taken together, these results indicate that no single energy substitution rate can simultaneously minimize all evaluated impact categories. However, the overall trends remain consistent across the analyzed range, suggesting that the study conclusions are robust to uncertainties in the share of renewable fuels. These findings are consistent with recent literature showing that the environmental performance of renewable fuels and dual-fuel systems depends not only on the substituted energy fraction, but also on fuel characteristics, energy vector production pathways, and the operating conditions of energy conversion systems (Ajeeb et al., 2025; Alves et al., 2025; Rodríguez-Fernández et al., 2024).

Effect of feedstock and hydrogen production route on HVO production.

The assessment of HVO scenarios produced using different feedstocks and hydrogen supply pathways allowed us to identify the main drivers of variations in environmental impacts. The results presented in Figure 21 indicate that differences related to the feedstock used for fuel production were generally more significant than those associated with replacing fossil-derived hydrogen with green hydrogen, although the influence of each factor varied depending on the impact category considered.

Among the evaluated categories, FRS was the most sensitive to the replacement of fossil hydrogen with green hydrogen. A consistent reduction in impacts was observed across all scenarios when green hydrogen was adopted. Although hydrogen represents a relatively small fraction of the total HVO inventory in mass terms, its production is energy-intensive and highly dependent on fossil resources when produced via natural gas steam reforming. Consequently, even small changes in this stage are directly reflected in indicators related to fossil resource consumption. Similar findings were reported by (Ajeeb et al., 2025), who identified hydrogen production as one of the main contributors to the environmental impacts associated with HVO production. Likewise, (Osman et al., 2024) highlighted reductions in fossil fuel dependence as one of the main environmental benefits of electrolytic hydrogen pathways powered by renewable energy sources.

On the other hand, the comparison between HVO produced from UCO and rapeseed oil revealed more pronounced differences across several environmental categories. Scenarios based on rapeseed oil consistently showed higher impacts than those based on UCO across nearly all evaluated categories, particularly GWP, OF, HT, and ET. This behavior is mainly related to agricultural activities associated with rapeseed cultivation, including fertilizer and pesticide application, soil preparation, fuel use in mechanized operations, and biomass processing. By contrast, UCO is treated as a residual feedstock, avoiding agricultural production stages and allocating environmental burdens across existing production systems. Previous studies have also reported superior environmental performance for waste-based HVO

pathways compared with feedstocks cultivated specifically for biofuel production (Ajeeb et al., 2025; Xu et al., 2022).

For the GWP and OF categories, replacing fossil-derived hydrogen with green hydrogen resulted in relatively small changes compared with the differences observed between feedstocks. Although renewable hydrogen reduces impacts associated with its production stage, part of this benefit is offset by the logistical processes considered in this study, including land transportation to the Port of Santos and maritime transport to Spain. These results suggest that impacts in these categories are more strongly influenced by the feedstock supply chain than by the hydrogen production pathway itself.

The Fine Particulate Matter Formation, Human Toxicity, and ET categories showed limited sensitivity to hydrogen substitution but more noticeable differences between feedstocks. This indicates that the main contributors to these impacts are associated with the production and processing stages of the oils used in HVO production, whereas the hydrogen production pathway accounts for only a relatively small share of the total impact.

In summary, the results indicate that replacing fossil-derived hydrogen with green hydrogen contributes to reducing dependence on fossil resources but leads to only limited changes across most of the evaluated impact categories. By contrast, feedstock selection was a key factor that influenced the environmental performance of HVO. Scenarios based on UCO consistently showed significantly lower impacts than for HVO produced from rapeseed oil, suggesting that the environmental benefits associated with using waste-based feedstocks can exceed the benefits achieved solely through changes in the hydrogen production pathway. The findings, therefore, suggest that strategies aimed at expanding HVO production should focus on both decarbonizing energy inputs and prioritizing feedstocks with lower environmental burdens throughout their life cycle.

3.4. Conclusions

This study applied a spatially explicit LCA to evaluate green hydrogen production in Minas Gerais, its export to Europe, and its use in dual-fuel internal combustion engines to generate electricity. By integrating regionalized production, international logistics, and end-use applications, the analysis identified the main hotspots across the hydrogen and hydrogen derivatives value chain, highlighting the importance of a life cycle perspective when assessing decarbonization strategies.

The results showed that the environmental performance of the evaluated systems depends not only on emissions generated during engine operation, but also on upstream stages related to fuel production, storage, transportation, and conditioning. Overall, HVO scenarios that employed UCO had the best environmental performance, with substantial reductions in GWP (85%), FRS (74%), and toxicological impacts (44%) compared to conventional diesel.

Of all evaluated alternatives, the scenario based exclusively on HVO had the best overall environmental performance. It also showed the lowest impacts in the GWP, fossil resource scarcity, human toxicity, and ET categories, since this scenario avoids additional burdens associated with producing, storing, transporting, and conditioning intermediate energy carriers like hydrogen, methanol, and ammonia. These findings show that HVO produced from is a strong candidate for decarbonizing electricity generation systems that employ internal combustion engines. Among the hydrogen-based alternatives, the HVO-compressed hydrogen pathway emerged as the best-performing configuration in most environmental categories, reducing impacts by between 17% and 79% relative to conventional diesel.

The environmental performance of electrolysis-based hydrogen production was strongly influenced by the electricity source. Biomass-based electrolysis had the lowest GWP and FRS impacts, while PV-powered electrolysis showed more favorable performance in the air quality and toxicity categories. These findings highlight the importance of considering regional characteristics and supply chain specificities when developing strategies for green hydrogen production.

Despite reducing reliance on fossil fuels, methanol- and ammonia-based pathways exhibited significant environmental trade-offs. Additional fuel conversion and conditioning stages increased impacts in several categories, with methanol performing worst in toxicity-related categories and ammonia in fine particulate matter formation. Moreover, ammonia did not achieve net climate benefits because N₂O emissions from engine operation offset the reductions in CO₂ emissions associated with partial fossil fuel substitution.

The sensitivity analysis confirmed the robustness of the study's main conclusions. It showed that, although impact magnitudes vary according to the energy substitution rate, the overall trends remain consistent with respect to both the origin of the hydrogen used in HVO production and the selected feedstock. The results show that feedstock selection has a greater influence on the environmental performance of HVO than replacing fossil-derived hydrogen with green hydrogen across several impact categories. This finding reinforces the importance of prioritizing waste-based feedstocks, e.g., UCO, over raw materials cultivated specifically for energy production. Finally, the results demonstrate that alternative fuels should not be selected merely by considering their GHG reduction potential; rather, multiple environmental impact categories should be considered simultaneously. Overall, this study contributes to the development of more sustainable strategies for producing, transporting, and using green hydrogen and renewable fuels, while also providing relevant insights for planning future international low-carbon fuel supply chains.

4 General discussion and Conclusions

4.1. Complementary perspectives on green hydrogen planning

This dissertation addressed the green hydrogen production and use through two complementary perspectives . The first study focused on identifying the most suitable regions for green hydrogen production in the state of Minas Gerais through the integration of Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP), considering technical, environmental, infrastructural, and socioeconomic criteria. The second study expanded this territorial perspective by evaluating the environmental performance of alternative hydrogen supply chains using a spatially explicit Life Cycle Assessment (LCA), encompassing hydrogen production in Minas Gerais, international transport to Europe, and electricity generation in dual-fuel internal combustion engines.

Both studies investigate green hydrogen systems, and they address different but complementary research questions. The first article seeks to determine where hydrogen production should be located by balancing multiple territorial criteria, whereas the second evaluates how hydrogen should be produced, transported, and utilized from an environmental perspective. Consequently, the integration of both approaches provides a broader framework for supporting strategic decision-making than either methodology could achieve independently.

A common aspect evaluated by both studies is the environmental and technical trade-offs. In the territorial assessment, the main trade-off lies between regional suitability and technical hydrogen production potential. Regions with abundant renewable resources are not necessarily the most suitable for hydrogen deployment once environmental restrictions, infrastructure availability, water resources, and socioeconomic conditions are simultaneously considered. Similarly, the life cycle assessment demonstrated that hydrogen supply chains presenting lower greenhouse gas emissions do not necessarily achieve the best overall environmental performance across all impact categories. Fuel conditioning processes, transportation requirements, feedstock selection, and combustion characteristics introduce additional environmental burdens that must also be considered.

These findings demonstrate that sustainable hydrogen planning requires a systems perspective capable of integrating territorial, technical, and environmental dimensions. Decisions based exclusively on renewable resource availability may overlook important territorial constraints, whereas decisions based solely on climate change mitigation may shift environmental burdens to other impact categories. Therefore, the combined application of spatial multicriteria analysis and spatially explicit life cycle assessment represents a robust methodological framework for supporting public policies, infrastructure planning, and investment decisions related to the development of green hydrogen supply chains.

4.2. Trade-offs in territorial suitability assessment

One of the main challenges associated with the planning for a green hydrogen supply-chain is identifying the most suitable locations for production while simultaneously considering multiple territorial constraints. This aspect was addressed in Chapter 2. Unlike approaches based exclusively on renewable resource availability, the proposed methodology integrated 22 subcriteria grouped into four major dimensions—resource availability, environmental aspects, infrastructure availability, and regional development—using the Analytic Hierarchy Process (AHP) combined with Geographic Information Systems (GIS). The criteria and their relative importance were established through consultations with more than sixty stakeholders from academia, industry, and government, resulting in a decision framework specifically adapted to the characteristics of Minas Gerais.

The results demonstrate that territorial suitability cannot be interpreted as a direct measure of hydrogen production potential. Although renewable resource availability is an essential prerequisite for electrolysis-based hydrogen production, it represents only one of several factors influencing the feasibility of project implementation. This distinction arises because technical potential is primarily determined by the availability of renewable electricity resources, whereas territorial suitability additionally incorporates environmental restrictions, land use, water availability, infrastructure, and socioeconomic conditions. Therefore, maximizing hydrogen production alone does not necessarily lead to the most appropriate territorial planning strategy. Nevertheless, the regions selected for the environmental assessment simultaneously exhibited high territorial suitability and high production potential within each supply chain route analyzed. Table 5 summarizes the AHP suitability scores and the estimated hydrogen production potential for the selected regions associated with the PV, Wind, and Biomass routes, enabling the development of representative scenarios for the state of Minas Gerais.

Table 5 - Territorial suitability scores and technical hydrogen production potential of the routes included in the spatially explicit life cycle assessment.

Route	Region	Route-specific AHP score	Overall AHP score	Overall AHP ranking	Route-specific H ₂ production potential (Mt H ₂)
PV	Paracatu	0.68	0.64	5°	2.02
Wind	Uberlândia	0.76	0.71	1°	0.47
Biomass	Uberlândia	0.72	0.71	1°	0.02

This finding reinforces the importance of integrating multicriteria decision-making methods into hydrogen planning. Previous studies applying AHP-GIS methodologies in Morocco (Amrani, 2024), Tunisia (Rekik, 2024), Thailand (Ali, 2022), Cameroon (Flora, 2025), Pakistan (Amjad, 2024), Chile (Cárdenas et al., 2026b) and the Brazilian state of Bahia (Governo do Estado da Bahia, 2023; Rocha, 2023) similarly demonstrated that suitable locations depend on the simultaneous evaluation of multiple technical and environmental criteria. However, most of these studies focused primarily on identifying

suitable areas and did not compare territorial suitability with independently estimated hydrogen production potential. By combining both analyses within the same framework, the present study demonstrates that these two indicators provide complementary rather than redundant information, allowing decision-makers to distinguish regions that combine favorable territorial characteristics with high production capacity.

Another contribution of this study concerns the procedure adopted to define the weighting factors. Although AHP has become one of the most widely used multicriteria methods for renewable energy planning because of its transparency and flexibility (Saaty, 2008), the results are inherently influenced by the subjective judgments used to assign weights to each criterion. Rather than defining these weights exclusively from literature or the research team, this study relied on a broad stakeholder consultation involving representatives from academia, industry, and public institutions. This participatory approach increases the representativeness of the weighting process and ensures that the suitability assessment reflects the priorities of actors directly involved in the emerging hydrogen sector in Minas Gerais.

Nevertheless, the subjective nature of AHP remains one of its principal limitations. Different stakeholders may attribute different levels of importance to environmental preservation, infrastructure, or renewable resources, potentially modifying the ranking of candidate regions. To address this limitation, sensitivity analyses were performed by varying both the relative importance of the four main criteria and the resource-related subcriteria. Although local changes in ranking were observed under alternative weighting configurations, regions such as Uberlândia and Paracatu consistently remained among the most suitable locations. This stability suggests that the proposed framework is sufficiently robust to support strategic planning while explicitly acknowledging the uncertainty associated with multicriteria decision-making.

The spatial patterns identified in this study are consistent with the current expansion of renewable energy and the emerging hydrogen economy in Minas Gerais. The priority microregions—including Uberlândia, Araxá, Paracatu, and Pirapora—coincide with areas characterized by rapid growth in photovoltaic generation and strategic industrial activities. This agreement is also reflected in the state hydrogen roadmap developed by CEMIG, (2025), which identifies Minas Gerais as one of Brazil's most promising regions for green hydrogen production through a distributed multi-hub strategy. In particular, Araxá and Paracatu host large-scale mining operations with significant energy demand (CBMM, 2024; KINROSS GOLD CORPORATION, 2023), while Uberlândia benefits from its strategic logistics network and agribusiness sector. The consistency between the proposed suitability model and state and national initiatives, including the Brazilian National Hydrogen Program (MME, 2021), FIEMG (2023), and the Ten-Year Energy Expansion Plan (EPE, 2024), provides additional confidence that the methodology captures not only theoretical renewable resource availability but also territorial characteristics that are directly relevant to the practical implementation of green hydrogen projects.

These findings also demonstrate that AHP-based suitability assessments are inherently context-dependent, since the relative importance of the evaluation criteria reflects regional environmental, infrastructural, socioeconomic, and institutional conditions. Consequently, results obtained for Minas Gerais should not be directly extrapolated to other regions. In the specific context of Minas Gerais, environmental constraints emerged as one of the most influential factors in defining territorial suitability, highlighting that renewable resource availability alone is insufficient to identify priority areas for green hydrogen production. This explains why the northwestern microregions combined the highest suitability scores with high production potential, whereas some resource-rich regions were ranked lower because of territorial constraints.

4.3. Trade-offs in the environmental performance of hydrogen supply chains

The second stage of this dissertation evaluated the environmental performance of alternative green hydrogen supply chains through a spatially explicit LCA, considering hydrogen production in Minas Gerais, international transportation to Europe, and electricity generation in stationary dual-fuel internal combustion engines. Unlike conventional LCA studies that frequently prioritize greenhouse gas emissions, the present assessment simultaneously considered climate change, fossil resource scarcity, air quality, and toxicity-related impact categories. This broader perspective allowed the identification of important environmental trade-offs associated with the production, conditioning, transportation, and final use of hydrogen and hydrogen-derived fuels.

The LCA results revealed that the partial substitution of diesel with hydrogen does not necessarily lead to the best overall environmental performance. Although the hydrogen-based scenarios reduced greenhouse gas emissions by approximately 16–24% compared with conventional diesel operation, part of these benefits was offset by the environmental burdens associated with hydrogen production, conditioning, and transportation. In this context, the HVO-based scenarios achieved the most favorable environmental performance. As shown in Table 6, the pathway based exclusively on HVO produced from used cooking oil (UCO) exhibited the best overall environmental performance across the evaluated impact categories. The HVO–compressed hydrogen scenario ranked second, standing out particularly in impact categories related to air quality. Similar environmental trade-offs have been reported by previous life cycle assessments of hydrogen supply chains. Schomberg et al., (2022) demonstrated that pathways with lower greenhouse gas emissions may exhibit higher impacts in toxicity- and resource-related categories depending on electricity supply and hydrogen conditioning processes. Likewise, Shi; Yan, (2024) showed that the environmental performance of green hydrogen strongly depends on electricity sources and transport configurations, reinforcing the importance of evaluating multiple impact categories when comparing alternative hydrogen systems.

Table 6 - Environmental performance of the diesel, HVO, and H₂-HVO scenarios across the impact categories assessed.

Category ¹	Diesel	HVO / UCO	HVO/ Rape oil	H ₂ -HVO (THH)			Unit
				PV	Wind	Biomass	
GWP	6.44E-01	9.51E-02	4.69E-01	1.31E-01	1.29E-01	1.08E-01	kg CO ₂ eq
FRS	2.06E-01	5.30E-02	1.09E-01	5.33E-02	5.28E-02	4.47E-02	kg oil eq
FPMF	1.17E+00	8.25E-01	1.88E+00	6.38E-01	7.86E-01	9.94E-01	g PM _{2.5} eq
OF	1.73E+01	1.36E+01	1.66E+01	8.62E+00	8.90E+00	1.17E+01	g NO _x eq
HT	6.19E-02	4.89E-02	6.76E-01	5.47E-02	5.32E-01	4.44E-01	kg 1,4-DCB
ET	3.25E-01	1.81E-01	1.47E+00	3.01E-01	2.36E+00	1.60E+00	kg 1,4-DCB

A green-to-red color gradient was used to facilitate interpretation of the results, where green represents the lowest impact and red the highest impact within each impact category.

The results also revealed important differences among the hydrogen transport and conditioning pathways. As pointed out in Chapter 3, routes requiring additional processing steps, such as liquefaction, ammonia synthesis, or methanol production, exhibited higher environmental impacts due to increased energy consumption and additional logistical operations. Compared with compressed hydrogen, liquefied hydrogen resulted in only marginal increases, generally below 5% across the impact categories evaluated. In contrast, ammonia showed the highest impacts in climate change and fossil resource scarcity, with increases of approximately 9–10%, while ozone formation increased by about 190% and fine particulate matter formation increased approximately 17-fold due to higher engine-out emissions. Methanol, on the other hand, exhibited the highest impacts in the human and environmental toxicity categories, increasing these impacts by up to 20% and 50%, respectively, mainly due to the additional synthesis processes required for fuel production. These findings reinforce that the sustainability assessment of green hydrogen should encompass the entire supply chain, from production to end use, rather than focusing solely on emissions associated with the combustion stage. This result also illustrates one of the central trade-offs identified in this dissertation: hydrogen carriers that facilitate storage and long-distance transportation are not necessarily those with the lowest environmental impacts. Consequently, selecting a hydrogen supply chain requires balancing logistical feasibility with overall environmental performance.

Another relevant aspect concerns the robustness of these findings under the sensitivity analyses performed. When used cooking oil (UCO) was replaced by rape oil as the feedstock for HVO production, environmental impacts increased in several categories due to the agricultural processes associated with dedicated biomass cultivation. Nevertheless, the HVO-based scenarios remained competitive compared with most of the hydrogen pathways evaluated. This finding is particularly relevant in the European context, where HVO is currently produced predominantly from waste-based feedstocks, especially used

¹ **Abbreviations:** GWP, Global Warming Potential; FRS, Fossil Resource Scarcity; FPMF, Fine Particulate Matter Formation; OF, Ozone Formation; HT, Human Toxicity; ET, Environmental Toxicity.

cooking oil and animal fats (Van Grinsven, 2020), although the use of virgin vegetable oils still occurs in some regions. Consequently, the environmental performance of HVO depends strongly on feedstock availability and sustainability criteria adopted by the fuel supply chain. This result indicates that the environmental advantages observed are not exclusively attributable to the attributional LCA assumption that used cooking oil is treated as a residual feedstock, to which no upstream environmental burdens from virgin vegetable oil production are allocated. Instead, the HVO-based scenarios remained competitive even when a dedicated crop (rape oil) was considered, demonstrating that their favorable environmental performance is also associated with the characteristics of the HVO production and utilization chain. Therefore, the sensitivity analysis demonstrates that the main conclusions are robust to changes in HVO feedstock, as the HVO-based scenarios remain environmentally competitive relative to the hydrogen–diesel pathways evaluated.

Despite the contributions of this study, some limitations should be acknowledged. The environmental assessment was conducted using an attributional LCA, which does not capture indirect consequences of large-scale green hydrogen deployment, such as changes in electricity supply, infrastructure expansion, or market dynamics. In addition, the analysis focused on a representative supply chain connecting Minas Gerais, Brazil, to Spain, considering technologies that are currently commercially available or at advanced stages of development. Consequently, the environmental performance reported here may differ under alternative export routes, future electricity mixes, or technological advances in electrolysis, hydrogen conditioning, and maritime transportation. These limitations should be considered when extrapolating the present findings to future large-scale hydrogen markets.

The European scenario adopted in this study is representative of current hydrogen transition strategies. Spain has positioned itself as one of Europe's leading renewable hydrogen hubs through its National Hydrogen Roadmap (MITERD, 2020) and the REPowerEU strategy (European Commission, 2022), which envisage large-scale hydrogen production, imports, and utilization to decarbonize industry and the energy sector. Although hydrogen is expected to be primarily consumed in hard-to-abate sectors such as steel, chemicals, and heavy transport, its application in stationary power generation is also regarded as a strategic option for providing dispatchable renewable electricity, seasonal energy storage, and flexibility services within highly renewable power systems. Therefore, the scenario considered in this study represents a realistic future.

The technologies assessed in this study are not hypothetical solutions but rather alternatives that are already commercially available or at advanced stages of development (Net Zero Technology Centre, 2024; TuluHong et al., 2024). Therefore, the findings have practical relevance for the decarbonization of electricity generation based on internal combustion engines (ICEs). Despite the rapid expansion of renewable energy sources in Europe, ICEs continue to play an important role in distributed generation, combined heat and power applications, and power system flexibility services (Dobre; Costin;

Constantin, 2024). Within this context, the HVO/UCO and HVO/UCO + compressed hydrogen scenarios stood out for combining high environmental performance with a high level of technological maturity. While the direct use of HVO can be implemented with minimal modifications to existing engines, the gradual introduction of hydrogen in dual-fuel configurations represents a viable strategy for reducing fossil fuel consumption and decarbonizing existing assets without requiring the complete replacement of installed infrastructure. These results demonstrate that the scenarios identified as environmentally preferable are also among the most feasible options for near-term implementation, reinforcing the practical relevance of the proposed assessment for supporting the transition toward low-carbon electricity generation.

4.4. Integration of both studies

The main contribution of this dissertation is the integration of territorial suitability assessment, technical hydrogen production potential, and spatially explicit LCA into a single decision-support framework for green hydrogen planning. Rather than conducting these analyses independently, the results of the multicriteria spatial assessment directly supported the definition of the LCA scenarios. Consequently, the environmental assessment was based on regions simultaneously presenting high territorial suitability and significant production potential, ensuring realistic implementation conditions instead of hypothetical production sites. By incorporating regional differences in renewable resource availability, infrastructure, and transport logistics, the proposed framework provides a more representative assessment of future hydrogen supply chains than conventional geographically averaged LCAs.

From a planning perspective, integrating territorial, technical, and environmental information enables decision-makers to evaluate hydrogen projects beyond renewable resource availability or greenhouse gas emissions alone. This systems approach supports a more comprehensive assessment of the multiple trade-offs involved in hydrogen supply chains, including territorial feasibility, production capacity, logistics, and overall environmental performance. As such, the proposed methodology provides a robust framework for supporting both public policies and industrial investment decisions.

When the results of the territorial suitability assessment, technical hydrogen production potential, and environmental life cycle assessment are considered together, the integrated analysis indicates that the most promising pathway among the scenarios evaluated consists of green hydrogen production by photovoltaic-powered water electrolysis in the Paracatu microregion, followed by its transportation to Spain in the form of compressed hydrogen and subsequent use in dual-fuel internal combustion engines operating with HVO as the pilot fuel for electricity generation. This pathway combines high territorial suitability, substantial hydrogen production potential, superior environmental performance, and high technological maturity, making it a realistic near-term strategy for supporting the decarbonization of distributed electricity generation.

4.5. Future research

The findings of this dissertation provide several opportunities for future research aimed at improving the planning and environmental assessment of green hydrogen supply chains. The following research directions are particularly recommended:

- Expanding the territorial suitability assessment to other Brazilian states and evaluating additional international hydrogen export routes.
- Applying prospective and consequential Life Cycle Assessment (LCA) approaches to evaluate future technological developments and market effects.
- Assessing additional hydrogen carriers and end-use applications beyond stationary dual-fuel internal combustion engines.
- Integrating environmental assessment with techno-economic analysis to support decision-making based on both environmental and economic criteria.
- Evaluating future scenarios considering changes in electricity mixes, transportation distances, and hydrogen demand.

Publications during Master course

- **Book Chapter:** Author, in collaboration with Rafael Capaz and Samara Azevedo, of the chapter *“Mercado Global e Estratégias para o Hidrogênio de Baixo Carbono”*, included in the book *Hidrogênio Verde – A Chave da Transição*, published by Interciência LTDA.
- **Conference Paper:** Author of the paper *“Spatial Assessment of Green Hydrogen Production Potential in Minas Gerais”*, presented at the 4th Brazilian Hydrogen Congress.
- **Published Journal Article:** *“Supporting Green Hydrogen Planning Through Spatial Multi-Criteria and Technical Potential Analysis”*.
- **Journal Article to be submitted:** *“Brazilian Green Hydrogen as a Diesel Replacement in Europe: A Spatially Explicit Life Cycle Assessment”*.

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