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THEORETICAL POTENTIAL OF GREEN HYDROGEN PRODUCTION FROM BIOMASS IN MINAS GERAIS

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Abstract. *This paper aims to present the theoretical potential of green hydrogen production from biomass in Minas Gerais, Brazil. The main limitations to achieve the theoretical potential of green hydrogen production from biomass are discussed. The technological pathway for green hydrogen production considers electricity generation from biomass combustion and proton exchange membrane electrolyzers. The biomass considered in potential for green hydrogen production were coffee, sugar cane (and vinasse), corn, soy, wood, and animal liquid manure. The amount of biomass was based on IBGE 2020-year production data. The methodology for the calculation of the electricity generation potential from the different biomass considered was exposed in the “Biomass Atlas of Minas Gerais”. This methodology for the above analysis uses the annual production, the thermal efficiency of the electricity generation system, the lower heating value, density, and other biomass parameters. Later the green hydrogen production was estimated using the hydrogen generation index of the Silyzer 300 electrolyzer. The results of the calculations show a theoretical potential of hydrogen production from coffee, sugar cane (and vinasse), corn, soy, wood, and animal liquid manure of 9.374.920,01 kg_{H2}/year, 90.029.226,60 (and 27.742.056,63) kg_{H2}/year, 80.089.123,44 kg_{H2}/year, 28.538.453,67 kg_{H2}/year, 68.746.448,70 kg_{H2}/year, 104.001.143,04 kg_{H2}/year, respectively. From these results it can be concluded that the theoretical potential of green hydrogen production in Minas Gerais is considerable (more than 408 million kg_{H2}/year) and that despite the limitations until reaching real production the state of Minas Gerais can become a relevant producer of green hydrogen in the national economy.*

Keywords: *Green Hydrogen, Theoretical potential, Biomass, PEM Electrolyzer.*

1. INTRODUCTION

Green hydrogen, which is produced from renewable sources, can play a key role in the transition to a more sustainable economy. For this reason, the estimation of the potential of green hydrogen production has been the subject of different studies in countries around the world.

Recently, Gandhi, et al. (2022) projects future adoption potential of green hydrogen from photovoltaic cells and electrolyzers, including several sectors and their expenditures in the United Arab Emirates. This work note that green hydrogen use for ammonia production represents the most promising contender for H₂ adoption representing a demand about 1 MMt in 2050 and cost competitiveness between 2022 and 2032. In the second ranking place is the use of green hydrogen in oil refining industry which demands could reach 0.5 MMt in 2050 and viability between 2023 and 2038.

For the Jordan case Jaradat, et al. (2022) discuss the potential of producing green hydrogen. They focus on the south region of the country due to its proximity to a water source using photovoltaic cells and polymeric electrolyte membrane electrolyzers. Using a MATLAB model, the authors estimate in 70.956 million kg the hydrogen production.

For the ECOWAS (Economic Community of West Africa States), Ballo, et al. (2022) analysed the barriers for developing the green hydrogen production and said that green hydrogen has the potential to alter the ECOWAS regions’ economic and political structure in ways more profound than any previous energy options. They empathize that a clear regulatory, policy and legal framework that supports and enables its deployment is needed to make this happen.

In the west Africa region, Bhandari (2022) analyzed the green hydrogen production for the case of Niger from photovoltaic cells solar electricity generation and electrolysis. The analysis considers the use of 5, 10 and 15% of land area and estimates an electricity generation amount about 979 - 2938 TWh with a green hydrogen production potential around 17.79 – 81.30 million tons per year in dependence of the land used area.

For the Turkey case, Karayel, et al. (2022) estimate the green hydrogen production from solar energy using monocrystalline and polycrystalline photovoltaic cells coupled with proton membrane and solid oxide electrolyzers. The results show that Erzurum, Konya, Sivas, and Vans are found to be the highest hydrogen production potential. For Turkey was estimated the total hydrogen production to be between 415.48 and 427.22 million tons, depending on the type of electrolyzer.

For developing the hydrogen economy in Pakistan Gondal, et al. (2018) estimate the potential of green hydrogen production from different renewable energies like solar, wind, geothermal, biomass and municipal solid waste. They conclude that biomass is the most feasible feedstock for developing a hydrogen supply chain in that country with a potential to generate 6.6 million tons of green hydrogen annually, followed by solar energy using photovoltaic cells that has a potential to generate 2.8 million tons of green hydrogen annually and, in third place, municipal solid waste with a capacity of 1 million tons per year.

In the case of Nepal, Thapa, et al. (2021) studied the green hydrogen production potential from the surplus of hydropower energy aiming to replace of petroleum products in the transportation sector. The results show that the potential of green hydrogen production ranges from 63,072 tons to 3.153.360 tons with the utilization of surplus energy at 20% and 100% respectively in 2030.

For the Colombian case Rodríguez-Fontalvo, et al. (2023) state that it is possible to produce green hydrogen at a rate of 9 million tons per year in 2050 by installing 121 GW of electricity from renewable energy while processing 303 million tons per year of residual biomass. Accordingly, to the authors whit this amount Colombia could reach 1.2% of the green hydrogen global market with cumulative investment of over 244 billion United States dollars by 2050.

For the Ecuador case Posso, et al. (2023a) estimate the green hydrogen production potential and the impact of its uses. The total potential of green hydrogen production in Ecuador reaches 438 million tons/year based mainly from solar energy photovoltaic cells. The mentioned amount impact beneficial on the predicted demand, been enough for use as fuel and as chemical input.

Towards the hydrogen economy in Paraguay, Posso, et al. (2022b) show the greatest potential for green hydrogen production from solar and wind energy in the western region and from hydropower in the eastern region. The potential of green hydrogen production is about 22.5 million tons per year mainly (up to 90%) from solar energy using photovoltaic cells.

The use of nuclear power for green hydrogen production in India was assessed by Bhattacharyya, et al. (2022) and concluded that when coupled with water electrolyzers can produce annually 1.8 – 4 million tons of H₂ at competitive cost. The authors also estimates than green hydrogen production from nuclear power can meet between 6% and 15% of the current demand of priority sectors avoiding about 490 – 570 million tons of CO₂ in dependence of the end use sectors.

The use of green hydrogen for fueling very heavy vehicles in New Zealand, was studied by Perez, et al. (2021) and indicated a green H₂ demand of 71 million kg per year. The study established that the annual electricity generation potential renewable energy is about 9824 GWh which is greater than the required for the green hydrogen production (4492 GWh) to attend the mentioned H₂ demand. The calculated levelized hydrogen cost was NZD 6.83/kg which is equivalent to NZD 0.55/km. The study remarks that the electricity cost is the most sensitive cost parameter for green hydrogen production.

Respect to the green hydrogen cost-potential for global trade, Franzmann, et al. (2023) done a detailed cost-potential curves for 28 selected countries worldwide until 2050, using an optimization energy system approach based on open-field photovoltaics cells and onshore wind. The results, Lower Heating Value (LHV) base, reveal a green hydrogen potential production higher than 1500 PWh_{LHV} per year and 79 PWh_{LHV} per year, using photovoltaics and wind energy respectively, at costs below 2.30 EUR/kg in 2050, dominated mainly by solar reach countries in Africa and Middle East.

As can be seen studies about green hydrogen production potential has been done recently in different countries and geographical regions. In the case of this paper, we aim to present the theoretical potential of green hydrogen production from biomass in Minas Gerais, Brazil. The idea of this objective came from the research project “FAPEMIG (PPM 00650-18, RED-00090-21, 64136)” which aim to estimate the green hydrogen production potential in Minas Gerais by different technological pathways like thermal solar energy electricity generation and electrolysis, biomass gasification coupled with electricity generation and electrolysis, biomass combustion coupled with electricity generation and electrolysis, etc. This paper focus in the last pathway mentioned above, which is the technological pathway for green hydrogen production considering electricity generation from biomass combustion and proton exchange membrane electrolyzers. The biomass contemplated in potential for green hydrogen production were coffee, sugar cane (and vinasse), corn, soy, wood, and animal liquid manure. The amount of biomass was based on IBGE 2020-year production data (IBGE, 2020). The methodology for the calculation of the electricity generation potential from the different biomass considered was exposed in the “Biomass Atlas of Minas Gerais” (Reis and Reis, 2017). At the end of the paper the main limitations to achieve the theoretical potential of green hydrogen production from biomass are discussed as well as some examples of the uses of green hydrogen.

2. METHODOLOGY

The estimation of green hydrogen production in Minas Gerais is based on the electricity generation from biomass for the PEM Electrolyzer hydrogen production. Firstly, the biomass production data is shown, later the equations for the estimation of electricity generation are presented. Those equations are based on the methodology “Biomass Atlas of Minas Gerais” (Reis and Reis, 2017). Finally, from the electricity generation the green hydrogen production is calculated using the PEM Electrolyzer Silyzer 300 production data.

2.1 Biomassa data

The availability of biomass for the calculation of the potential for green hydrogen production was extracted from the IBGE for the year 2020 and is shown in Table 1. From the production data presented, the methodology presented below calculates the estimated electricity generation. In the case of sugarcane, the amount of electricity that can be generated from the residual vinasse of the sugar and alcohol manufacturing process is also considered.

Table 1. IBGE biomass production data for 2020 year (IBGE, 2020).

Biomass	Production	Animal ⁽¹⁾	Heads
Coffee (ton)	2064689	Bovine	744887
Corn (ton)	7689309	Pig	423732
Soy (ton)	6218740	Poultry	266550
Sugar cane (ton)	78383655		
Wood (m ³)	13645977		

⁽¹⁾ used for the estimation of animal liquid manure.

2.2 Theoretical electricity generation potential from biomass

The electricity generation potential from the production of coffee, corn or soy is estimated by Eq. (1), which considers the annual production, the conversion factor in biomass, the useful heat value of the biomass in question, the availability collection factor and thermal efficiency or energy conversion factor of system for electricity generation.

$$\text{ElectricityGenPotential}_{\text{coffee, corn or soy}} (\text{MW}) = \frac{t_{\text{coffee, corn or soy}} \cdot F_C \cdot HVU \cdot F_D \cdot \eta}{8322 \cdot 860}, \quad (1)$$

In which:

$t_{\text{coffee, corn or soy}}$	Coffee, corn or soy production, in ton;
F_C	Conversion factor of ton of coffee, corn or soy to ton of biomass, equal to 1 for coffee, 2.2 for corn and 1.35 for soy;
HVU	Useful Heat Value, equal to 3399.8 kcal/kg for coffee, 3544.9 kcal/kg for corn, and 3393.7 kcal/kg for soy;
F_D	Availability collection dimensional factor, equal to 0.4, for coffee and corn, and 0.3 for soy;
η	Energy conversion dimensional factor, equal to 0.15;
8332	Operational hours per year;
860	Conversion factor, from kcal to kWh.

The electricity generation potential from the production of sugar cane is estimated by Eq. (2), and include the electricity generation potential from vinasse, given by Eq. (3). The electricity generation from sugar cane considers the sugar cane production and the electricity generation index, which in this case is adopted for a typical modern electricity generation system. The electricity generation from vinasse considers the conversion factors of sugar cane in ethanol, of ethanol in vinasse and the biogas per DQO (Oxygen Chemical Demand), as well as the lower heating value and the turbine efficiency.

$$\text{ElectricityGenPotential}_{\text{sugar cane bagasse}} (\text{MW}) = \frac{t_{\text{sugar cane}} \cdot 60 \text{ kW/t}}{1000 \cdot 5563}, \quad (2)$$

In which:

$t_{\text{sugar cane}}$	Sugar cane production, in ton;
60 kW/t	Electricity generation index per sugar cane ton;
5563	Season operational hours per year;
1000	Conversion factor, from kW to MW.

$$\text{ElectricityGenPotential}_{\text{vinasse}}(MW) = \frac{t_{\text{sugar cane}} \cdot F_{\text{ethanol}} \cdot F_{\text{vinasse}} \cdot DQO \cdot \eta_1 \cdot F_{\text{biogas}} \cdot LHV \cdot \eta_2}{8760 \cdot 860 \cdot 1000}, \quad (3)$$

In which:

$t_{\text{sugar cane}}$	Sugar cane production, in ton;
F_{ethanol}	Conversion factor of ton of sugar cane to ethanol liters, equal to 80 l/ton;
F_{vinasse}	Conversion factor of ethanol liters to vinasse liters, equal to 11.9 l/l;
DQO	Oxygen chemical demand, equal to 0.0029 kg/l
η_1	DQO remotion efficiency dimensional factor, equal to 0.717;
F_{biogas}	Biogas conversion for removed DQO, equal to 0.45 Nm ³ /kg;
LHV	Lower Heating Value, equal to 5100 kcal/Nm ³ ;
η_2	Turbine efficiency dimensional factor, equal to 0.35;
8760	Operational hours per year;
860	Conversion factor, from kcal to kWh;
1000	Conversion factor, from kW to MW.

The electricity generation potential from the production of woods, is mainly based on the eucalyptus production and is estimated by Eq. (4), which considers the annual production, the conversion factor in biomass, the useful heat value of the biomass in question, the availability collection factor, the thermal efficiency, or energy conversion factor of system for electricity generation and the eucalyptus density.

$$\text{ElectricityGenPotential}_{\text{eucalyptus}}(MW) = \frac{t_{\text{eucalyptus}} \cdot F_C \cdot HVU \cdot F_D \cdot \eta \cdot \rho}{8332 \cdot 860}, \quad (4)$$

In which:

$t_{\text{eucalyptus}}$	Eucalyptus production, in m ³ ;
F_C	Conversion factor of ton of eucalyptus to ton of biomass, equal to 0.5;
HVU	Useful Heat Value, equal to 3017.7 kcal/kg;
F_D	Availability collection dimensional factor, equal to 0.4, for coffee and corn, and 0.3 for soy;
η	Energy conversion dimensional factor, equal to 0.15;
ρ	Eucalyptus density, equal to 0.5 ton/m ³ ;
8332	Operational hours per year;
860	Conversion factor, from kcal to kWh.

The electricity generation potential from the animal liquid manure is estimated by Eq. (5), which considers for heads of bovine, pig, and poultry several indexes like produced manure, biogas production methane concentration and density and thermal efficiency or energy conversion factor of system for electricity generation.

$$\text{ElectricityGenPotential}_{\text{animal liquid manure}}(MW) = \frac{365 \cdot N \cdot Et \cdot Pb \cdot CH_4 \cdot LHV \cdot \eta}{\rho \cdot 8332 \cdot 860 \cdot 1000}, \quad (5)$$

In which:

365	Days of the year;
N	Animal amounts, in heads;
Et	Produced manure, equal to 10 for bovine, 2.25 for pig, and 0.18 for poultry in kg/(day.head);
Pb	Biogas production factor, equal to 0.037 for bovine, 0.062 for pig, and 0.055 for poultry in kg _{CH₄} /kg _{manure} ;
CH_4	Biogas methane concentration, equal to 0.60 for bovine and poultry and 0.66 for pig kg _{CH₄} /kg _{biogas}
LHV	Lower Heating Value, equal to 8604 kcal/Nm ³ ;
η	Energy conversion dimensional factor, equal to 0.28;
ρ	Methane density near to ambient conditions, equal to 0.74 kg/m ³ ;
8332	Operational hours per year;
860	Conversion factor, from kcal to kWh;
1000	Conversion factor, from kW to MW.

2.3 Estimation of hydrogen production

The estimation of annual hydrogen production by Eq. (6) is based on the electricity generation potential calculated by Eq. (1) to Eq. (5), considering the hydrogen production index of the PEM Electrolyzer Silyzer 300 at nominal capacity (Siemens, 2021).

$$H_2\text{ProductionPotential} \left(\frac{kg_{H_2}}{year} \right) = \text{ElectricityGenPotential} \cdot 19.143 \frac{kg_{H_2}}{MW} \cdot 8332, \quad (6)$$

In which:

8332 Operational hours per year.

In the next topic will be presented the potentials of electricity generation and green hydrogen production calculated from the methodology previously presented. A discussion about the results obtained and their limitations to be concretized in practice is established throughout the topic.

3. RESULTS AND DISCUSSIONS

Table 2 presents the amount of electricity generation potential from the different biomass sources considered in this work. According to these results the sugarcane has the highest potential for electricity generation followed by animal effluent, corn, and wood in this sequence, and finally soy and coffee.

Table 2. Electricity generation from de different biomass sources.

Biomass	Electricity Generation (MW)	Animal ⁽¹⁾	Electricity Generation (MW)
Coffee	58.848	Bovine	338.837
Corn	502.735	Pig	192.749
Soy	179.141	Poultry	121.249
Sugar cane	845.411		
Vinasse	165.440		
Wood	431.535	Total	2,835.945

⁽¹⁾ electricity generation from animal liquid manure.

Note that the total amount of electricity that could be potentially generated is considerable (~2.8 GW) and if all of it were available to produce green hydrogen, the amount of this that could be produced would be enormous as will be seen later. However, there are several issues that make all this potential cannot be harnessed. These issues are discussed below:

- Logistics of biomass collection for use as fuel. The biomass that has traditionally been used on a relatively large scale for electricity generation are sugar cane and wood. From sugar cane the electricity can be generated from sugarcane bagasse and vinasse. The use of sugarcane bagasse for the generation of electricity dates back more than a century and can be considered as something usual in the sugarcane sector since sugarcane bagasse is a residue of the sugarcane milling process. With vinasse there is no consolidated experience of its use for the generation of electricity, even when it is a residue of the alcohol manufacturing process. That is, both sugarcane bagasse and vinasse are collected as residues from the sugar and alcohol manufacturing process and are easily available for the generation of electricity which is made within the sugar and alcohol factories themselves. In the case of wood there is also a tradition in its use as a fuel for the generation of electricity. The collection of wood for use as fuel is not a problem in technological terms, but it can be a problem in terms of cost since wood, even in the case of forest waste, has costs associated with the collection and transportation to the electricity generation plants. Of the other biomasses considered, specifically coffee, soybeans, and corn, there is no tradition of its use as a fuel for electricity generation, although the technology of collecting and generating electricity can be shared. These biomasses also have costs associated with collecting and transporting them from fields or processing plants to electricity generation plants. In the case of animal effluents, the costs are associated with investments for the collection of animal effluents on farms. At first the generation of electricity from animal effluents would be or would have to be carried out on the farms themselves.

- Biomass dispersion. The biomass studied in this work is characterized by being widely dispersed throughout Minas Gerais with regions where one type of biomass is produced in greater quantity than another. For example, sugarcane production is concentrated more in the south-east region, while coffee is concentrated more in the southern region, while corn is practically distributed throughout the whole Minas Gerais territory. The dispersion of biomass becomes a problem in the case of Minas Gerais because of its large territorial area. Note that the dispersion of biomass is an issue linked to logistics, that is, given the dispersion of biomass, either it incurs high costs with collection and transport of biomass or whether it performs the generation of energy on a small scale according to the availability of biomass. The effect of biomass dispersion will translate into the economic unfeasibility of electricity generation in many cases and in others into the technological unfeasibility of electricity generation. Technological infeasibility must be understood in the context of the minimum amount of fuel that has to be burned to have an electricity generation system that can be built from existing technology and to operate a high number of hours per year (11 months). In the case of solid biomass (those considered except animal effluents) the minimum electricity generation capacities shall be derived from combustion systems with burning capacities greater than 0,03 kg/s of fuel. In the case of animal effluents, it depends on the methane flow that is produced in each of the farms.

- Generation of electricity committed to purposes other than the production of green hydrogen. Among the sources of biomass considered in this study, coffee, soybeans, corn, part of the wood and animal effluents could put their potential of electricity generation to produce green hydrogen since it does not generate significant electricity from these sources. In the case of sugar cane, it is different. In the sugar-alcohol sector, sugarcane bagasse is used extensively for electricity generation, sometimes only for own consumption, other times (mostly) for the electricity generation with cogeneration. For this reason, significant technological changes will be needed in the sugar and alcohol manufacturing process, and a significant modernization in electricity generation systems, to have an excess of electricity generated from sugarcane bagasse that can be used to produce green hydrogen. In the case of vinasse, given its non-existent use, it is possible to put the potential for electricity generation as a function of the production of green hydrogen. It may even be thought that through the production of green hydrogen is the initial incentive for the conversion of vinasse into electricity in the sugar-alcohol sector.

- Inexperience of biomass producers with electricity generation and the environment of the Brazilian electricity sector. The sugar-alcohol sector (whose sources of biomass are sugarcane bagasse and vinasse) has a consolidated experience of electricity generation and knowledge of the Brazilian electricity sector. The other agricultural sectors from which the other biomass sources considered in this study are derived have no experience in electricity generation and have little or no knowledge about the electricity sector. For these other sectors until the arrival of green hydrogen production, there was no interest in putting electricity generation as a business alternative, and it may be that this idea prevails given the expertise in the subject. It is to be expected that biomass producers do not have the equity to invest in electricity and green hydrogen generation systems located in their agricultural facilities. This time it is more interesting to think that the companies in the electricity sector will be dedicated to this purpose instead of biomass producers. In any case, a new environment and business models will be needed to develop electricity generation and the production of green hydrogen from biomass sources that are currently untapped.

Table 3 presents annual green hydrogen production potential from the different biomass sources considered in this work. According to these results the sugarcane has the highest potential for green hydrogen production followed by animal effluent, corn, and wood in this sequence, and finally soy and coffee.

Table 3. Annual green hydrogen production potential from de different biomass sources.

Biomass	Annual Green Hydrogen Production potential (kg)
Coffee	9,374,920.01
Corn	80,089,123.44
Soy	28,538,453.67
Sugar cane	90,029,226.60
Vinasse	27.742.056,63
Wood	68,746,448.70
Animal ⁽¹⁾	104,001,143.04
Total	408,521,372.09

⁽¹⁾ green hydrogen production potential from animal liquid manure.

Since electricity generation is the first step in producing green hydrogen via electrolysis, all the issues previously discussed are valid in terms of impediments to exploiting the full potential of green hydrogen production shown in Table 3. The following are mentioned and discussed some of the barriers encountered by the production of green hydrogen:

- Cost: The production of green hydrogen is currently more expensive compared to other forms of hydrogen production, such as gray hydrogen (produced from fossil fuels with carbon capture). The infrastructure needed to produce, store, and distribute green hydrogen is still expensive, which limits its large-scale economic viability.

- Scale and production capacity: Large-scale production of green hydrogen requires a significant amount of renewable energy. However, the availability and capacity of renewable energy generation may be limited in some regions. In addition, the infrastructure needed to produce green hydrogen on a large scale is still under development.

- Storage and distribution: Hydrogen is a low-energy density gas, which means it requires a lot of space for efficient storage and transportation. Currently, hydrogen storage and distribution infrastructure are in the early stages of development, which makes large-scale implementation difficult.

- Electrolysis technologies: The production of green hydrogen involves the use of electrolysis of water, which requires efficient and cost-effective technologies. Although electrolysis is commercially available, there is still room for improvement in terms of energy efficiency, durability, and cost. In the methodology adopted, it is assumed that the electrolyzer has a constant production capacity, which is not true because a drop in production must happen throughout the life of the electrolyzer.

- Policies and regulations: The lack of favorable policies and regulations can be a significant barrier to green hydrogen production. Government incentives, supportive policies, decarbonization targets and specific regulations are needed to boost the sector and create an enabling environment for investment and innovation.

- Public awareness and acceptance: The widespread adoption of green hydrogen also depends on public awareness and acceptance. Understanding the environmental and economic benefits of green hydrogen, as well as overcoming concerns related to safety, transportation, and storage, are important elements to promote its large-scale production and use.

Although these barriers exist, it is important to note that the production of green hydrogen has a variety of uses in different sectors as follows:

- Vehicle fuel: Hydrogen can be used as fuel in fuel cell vehicles, such as the Toyota Mirai, where it is combined with oxygen from the air to produce electricity, generating only water as a byproduct. These vehicles are known for their zero emissions and are a promising alternative to fossil fuel-powered vehicles. Hydrogen-powered vehicles have longer range and can be refueled quickly, offering a similar experience to conventional vehicles. They are the path to sustainable transport. An alternative is the use of green hydrogen as a blend in diesel vehicles, mainly in trucks and buses, thus reducing total emissions in the transport sector. This alternative use requires adaptations in the fuel injection system, but it is cheaper than a complete fuel cell engine.

- Power generation: Hydrogen can be used to generate electricity in power plants. It can be burned in a gas turbine, like other fossil fuels, or used in fuel cells to produce electricity more efficiently and cleanly.

- Energy storage: Hydrogen can be used to store renewable energy. The excess electricity generated by renewable sources, such as solar and wind energy, can be used to produce hydrogen through the electrolysis of water. This hydrogen can be stored and subsequently used to generate electricity when demand is high or when renewables are not generating enough power. This helps to solve the challenge of the intermittency of renewable energies.

- Chemical industry: Hydrogen is widely used in the chemical industry as a raw material. It is used in the production of ammonia, methanol, synthetic hydrocarbons, and various other chemicals. In addition, hydrogen can also be used to remove sulfur from fuels and process vegetable oils and fats.

- Oil refining: Hydrogen is used in the petroleum refining process to remove impurities, such as sulfur, and improve the quality of products, such as gasoline, diesel, and lubricating oils.

- Green hydrogen can be used as a clean energy source and as a feedstock in industry. It can replace hydrogen produced from fossil fuels, reducing carbon emissions associated with industrial processes such as the production of ammonia, methanol, petroleum refining, among others.

- Residential and commercial heating: green hydrogen can be used to provide energy for residential and commercial heating. It can be used in space heating systems, water heating and in industrial applications that require heat.

These are just a few examples of the uses of hydrogen. As research and development advances, new applications and technologies related to hydrogen are being explored, such as the use of green hydrogen (produced from renewable sources) to reduce greenhouse gas emissions and support the transition to a more sustainable economy.

4. CONCLUSIONS

The results of the calculations show a theoretical potential of hydrogen production from coffee, sugar cane (and vinasse), corn, soy, wood, and animal liquid manure of 9.374.920,01 kg_{H2}/year, 90.029.226,60 (and 27.742.056,63) kg_{H2}/year, 80.089.123,44 kg_{H2}/year, 28.538.453,67 kg_{H2}/year, 68.746.448,70 kg_{H2}/year, 104.001.143,04 kg_{H2}/year, respectively. From these results it can be concluded that the theoretical potential of green hydrogen production in Minas Gerais is considerable (more than 408 million kg_{H2}/year) and that despite the limitations, given by the reasons discussed in the text, until reaching real production the state of Minas Gerais can become a relevant producer of green hydrogen in the national economy.

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