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EVALUATION OF THE POTENTIAL FOR THE PRODUCTION OF RENEWABLE HYDROGEN BY SOLAR, WIND AND BIOMASS ENERGY: THE STATE OF PARANA

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Abstract. *The Intergovernmental Panel on Climate Change (IPCC) has pointed to the so-called "energy transition" from fossil fuels to renewable energy sources as the main path to lower emissions of greenhouse gases to attenuate atmospheric global warming and its impact on accelerating global climate change in reference to the pre-industrial era. That was called "decarbonization of the energy matrix". In order to achieve that and deal with intermittency and spatial distribution of solar and eolic energy as well as biomass to produce electricity (power), IPCC and the International Energy Agency project that until 2050 hydrogen is the substance that will make viable to integrate, balance and storage all those forms of energy sources. Part of those three energy resources will be used to produce hydrogen instead of producing power directly. The theoretical (primary) and technical potential to produce hydrogen is therefore key to planning the energy transition the countries committed to. This work presents a methodology to assess the theoretical and technical production potential of renewable hydrogen from solar, wind, and biomass residues as well as the economic viability and the environmental assessment in the Brazilian context. Departing from the irradiance for solar, mean wind speed, and agricultural biomass residue generation and converting factors for the many known routes and technologies, the potentials are estimated. All data were collected from the literature and public records. The case study for the State of Paraná is presented since it offers the complexities of time-spatial variation of insolation, sustained wind, and agricultural production while it has a decentralized population and economy. Results showed that the state of Paraná could produce an average of 93.029 ton/km²/yr of hydrogen from solar photovoltaic projects, 4.670 ton/km²/yr from eolic plants, and 26.647 ton/km²/yr from biomass residues. The regions with the greatest potential are Pioneer North by solar, West Center by eolic, then East Center by from biomass residues by gasification.*

Keywords: *Hydrogen, Decarbonization, Energy transition, Potential, Eolic, Solar, Biomass, Monte Carlo.*

1. INTRODUCTION

Nowadays, the key factor driving the transformations in the energy sector is sustainability in the sense of environmental issues related to concerns of the relatively the climate changes due to the relative rapid global warming caused by the relatively rapid rise in the greenhouse gasses in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) points out that such changes are mostly due to anthropic emissions related to energy conversion and changes in land use. Under this scenario, energy policies aim for energy systems that produce less greenhouse gasses (GHG) emissions that would eventually slow or limit the temperature rise on the planet (IEA, 2019).

The Paris Climate Agreement aims to limit the temperature rise to no higher than 2ºC above pre-industrial levels, with the main goal of limiting it to 1.5ºC until 2050. In order to reach that goal, the IPCC prescribes the full replacement of fossil fuels with renewable sources with null, low, or even negative, GHG emissions while dealing with intermittency and spatial distribution of energy sources as well as affordability. IPCC and the International Energy Agency (IEA, 2019) propose that renewable-origin hydrogen can be an energy carrier that would contribute to the energy transition while meeting the established constraints.

Renewable hydrogen is an important element in the energy transition since it can be used directly in heat engines (reciprocating engines or turbines) for electric power generation, in self-propelled transportation, but also as input for renewable hydrocarbon fuels such as biomethane or biomethanol when combined with CO_2, in the production of ammonia, in the steel making industry, in the intensification of bio-digestion, and energy storage (MME, 2020). Moreover, Brazil presents favorable conditions for solar, eolic, and biomass energy harvest that could foster the development of those sources for the production of renewable hydrogen and its final use for either the domestic or world market alike (de Oliveira, 2022).

This work then presents a methodology to assess the theoretical and technical potential for renewable hydrogen production derived from solar and eolic energy, and from residual agricultural biomass in the Brazilian context. The case study for the State of Paraná considers its meso regions, mostly set by their socio-economical profile, and the respective spatiotemporal variability of insolation, sustained wind, and agricultural residues production.

2. MATERIALS AND METHODS

In order to evaluate the renewable hydrogen potential in Paraná, we turned to the literature for available technologies and their respective conversion rates, climate (insolation and sustained wind) database, and public records for all three conversion pathways. For each parameter and when available, we consider their respective ranges and variability to perform an uncertainty analysis by the method of Monte Carlo, which was carried out in Python computer language. For each target output, the code performed 10,001 simulations with random combinations among them.

The variability of the input parameter and the results are shown in histogram charts.

The analysis of the Potential of Hydrogen in Paraná was performed by mesoregion of the state because this classification groups cities with physical and socioeconomic similarities (IBGE, 2023). The mesoregions of Paraná are: Northwest (NW), West Center (WC), North Central (NC), Pioneer North (PN), East Center (EC), West (W), Southwest (SW), South Center (SC), Southeast (SE) and Metropolitan Region of Curitiba (MRC).

2.1 Hydrogen Production Potential: Residual Biomass

Only dry solid agricultural (crops and forests) biomass residues were considered for hydrogen production. The potential of available biomass residue based on the agricultural year 2022/2023 was estimated by ranges of productivity in (kg/ha), the harvested land area in (ha) for each crop, then the respective residue-to-yield ratios and the available shares for conversion (de Souza *et al.*, 2021). All the potential biomass residue would be converted to hydrogen by gasification.

The reference technology for gasification was the dual fluidized bed (DFB) gasifier, since according to Ahlström (2020), it has been shown to be the most efficient for hydrogen production, that is, larger mean values for the conversion factor biomass to hydrogen in (gH_2/kgBS).

The uncertainty analysis took into account the conversion factor and the available dry biomass residue for energy conversion. For both parameters, the Monte Carlo method adopted normal probability distribution. Table 1 presents the adopted values for the conversion ratio. The range of variation of the available biomass for conversion was proportional to the minimum (-14.97%) and maximum (+30.66%) annual productivity in the last ten years in the State of Paraná (Fig. 3), while the range of variation of the conversion ratio factor from dry solid biomass to hydrogen via DFB gasifiers was between 30 to 150 gH_2/kgBS and a mean of 90 gH_2/kgBS.

Table 1. Conversion ratio factor from dry solid biomass to hydrogen via DFB gasifiers (Ahlström, 2020).

Conversion Factor (gH_2/kgBS)	**Value**
Minimum	30
Mean	90
Maximum	150

2.2 Hydrogen Production Potential: Solar Energy

The potential of electric solar energy generation (P_{pv}) in kWh per year is given by superficial solar irradiance (I_{solar}) em kWh/m^2, the potential PV-plants area (A_{pv}) in m^2, and the PV panel reference efficiency (η_{pv}), as proposed by Ishaq and Dincer (2021), and shown in Eq.(1).

$$P_{pv} = I_{solar} \times A_{pv} \times \eta_{pv} \quad (1)$$

The solar irradiance (I_{solar}) for each mesoregion was obtained from the *Paraná Meteorological System* (SIMEPAR, 2023). The data were modeled by the probability distribution of generalized extreme values (GEV), which combine in a sole form three kinds of GEV distributions, namely, Gumbel, Fréchet e Weibull (Malaquias *et al.*, 2020). The simulated solar irradiance for each mesoregion is shown in Fig. 5.

The potential solar energy generated (P_{pv}) would power a water electrolyzer to produce hydrogen. We adopted an alkaline electrolyzer, which according to Proost (2019), Saba *et al.* (2018), and Kotowicz *et al.* (2017) is the most promising technology in this pathway for delivering the lowest energy to hydrogen rates for electrolytic production (T_{pe}) in (kWh/kgH_2). The variability of that conversion factor is adopted to be a normal distribution centered at 52.5 kWh/kgH_2, with 45 and 68 kWh/kgH_2(Fig. 2), as ceiling and roof values, respectively Sigal *et al.* (2014). The hydrogen production potential from solar energy can then be obtained by Eq.(2).

$$H2V_{solar} = \frac{P_{pv}}{T_{pe}} \quad (2)$$

2.3 Hydrogen Production Potential: Wind Energy

In order to estimate the hydrogen production potential from wind, one needs to determine the sustained wind power potential, P_{wind} (W), in each mesoregion with some reference conversion technology and parameters. That is carried out by the formula presented in the *Atlas of the Wind Potential of the State of Paraná* (LACTEC-COPEL, 2018), Eq. (3).

$$P_{wind} = \frac{1}{2} \times \rho \times A_r \times v^3 \times C_p \times \eta_{wind} \quad (3)$$

where, ρ is the reference air density (Kg· m^{-3}), A_r is the swept area by the turbine rotor (m^{-2}) which is a function of the blade diameter (D), v is the mean sustained wind velocity (m·s^{-1}), C_p is the power aerodynamic coefficient of the rotor and η_{wind}, the overall generator assembly efficiency .

The eolic hydrogen potential would is computed based on the same electrolyzer utilized for the solar energy potential and a similar formula as well (Eq. (4).

$$H2V_{wind} = \frac{P_{wind}}{T_{pe}} \quad (4)$$

where, $H2V_{wind}$ is the annual potential of hydrogen production (kg), P_{wind} the projected annual electric energy generated kWh, e T_{pe} the hydrogen rate for electrolytic production in (kWh/kgH_2). The value of the parameters are found in Table 2 .

The uncertainty analysis for the eolic potential was based mostly on the sustained wind velocity for each mesoregion. The variability was modeled as Weibull probability distribution according to the Paraná Meteorological Agency SIMEPAR and Malaquias *et al.* (2020), (Fig. 4).

Table 2. Reference values adopted to estimate the eolic power generation potential.

Symbol	Value	Reference
ρ	1.225	Tiepolo *et al.* (2018)
D	45.000	Gnoatto (2017)
A_r	1590.431	-
v	variable as Fig. 4	SIMEPAR (2023)
C_p	0.550	LACTEC-COPEL (2018)
η	0.950	LACTEC-COPEL (2018)

3. RESULTS AND DISCUSSION

The results are presented according to the energy sources. The histograms of the main parameters of the Monte Carlo analysis are given in Figs. 1-4.

3.1 Hydrogen Production Potential: Residual Biomass

The annual hydrogen production potential from residual biomass is presented by its superficial density by the harvest land area for each one of the mesoregions in Fig. 6. The East Central (EC) region presents the highest theoretical average potential at 9.042 tonH_2/km^2/year, with a confidence interval (95) between 5.568 e 12.752 tonH_2/km^2/year. One of the main reasons is likely to be the great number of forest projects of Pinus and Eucalyptus and crops such as soybeans, corn, and beans, as well (CONAB, 2023). The variability seems reasonably high for energy biomass projects but it is a reflection of the diversity of residues, residue availability shares, and gasifier conversion efficiency.
The Monte Carlo Analysis Histogram of the Gasifier Conversion factor is shown in Fig. 1.

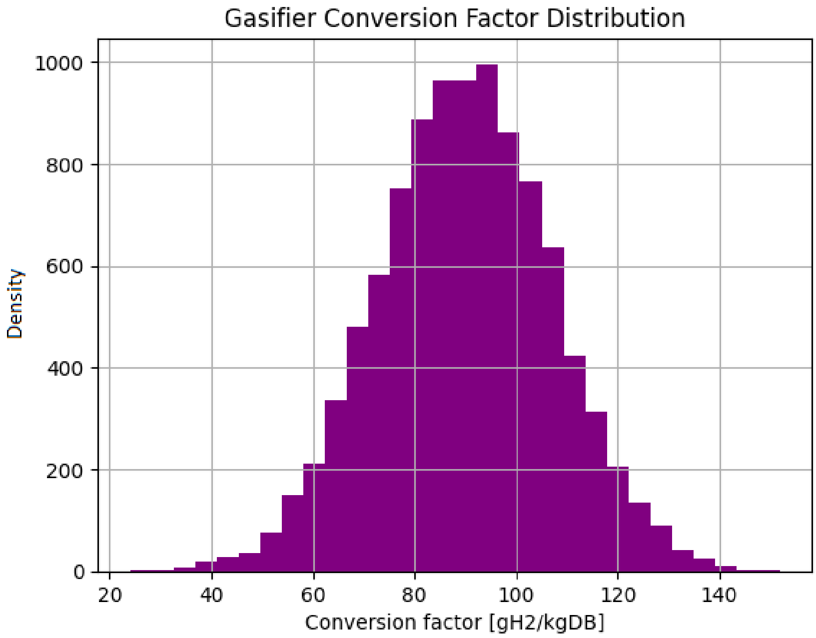

Figure 1. Histograms from the random simulations of conversion ratio factor from dry solid biomass to hydrogen via DFB gasifiers ($gH_2/kgBS$).

3.2 Hydrogen Production Potential: Solar Energy

The density of the annual hydrogen (H_2) theoretical production potential from solar energy by mesoregions of the State of Paraná, Brazil was computed by Eqs. (1) and (2) and it is presented in Fig. 7.

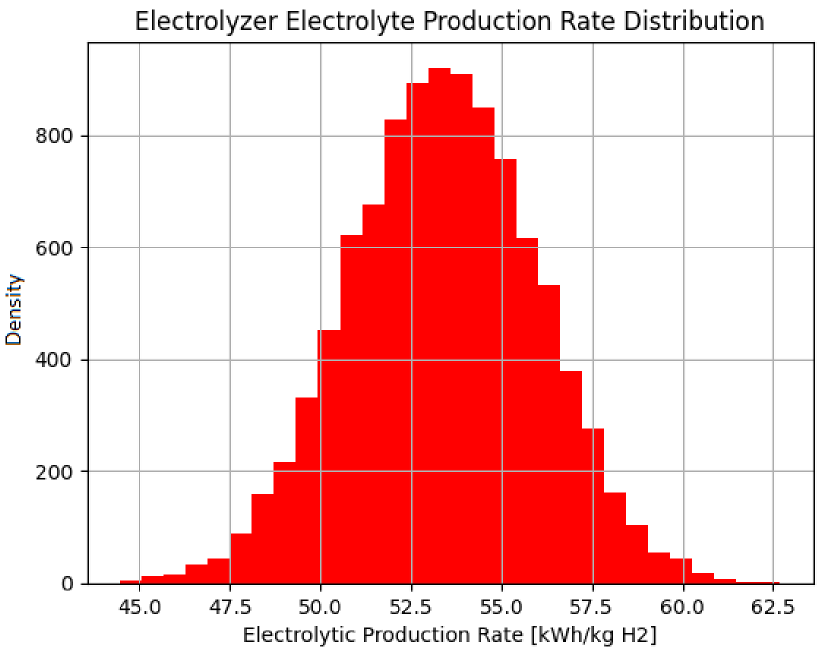

Figure 2. Histograms from the random simulations of the electrolyzer production rate in kWh/kgH_2.

The histograms of the Monte Carlo Analysis of Agroforestry Biomass available in Paraná are shown in Fig. 3.

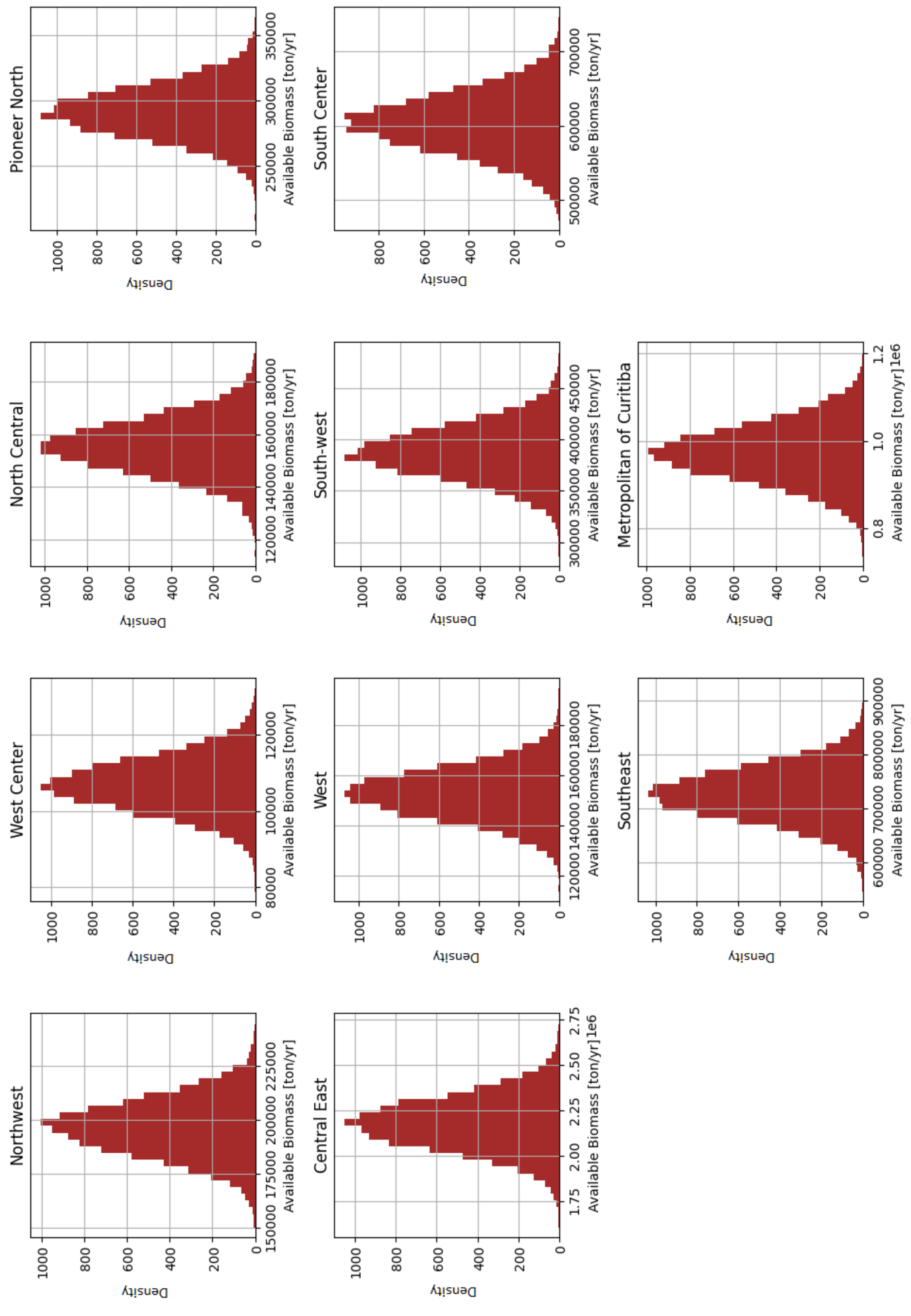

Figure 3. Histograms from the random simulations of dry solid biomass residues from agriculture and forests available for gasification ton/year, for all mesoregions of the State of Paraná

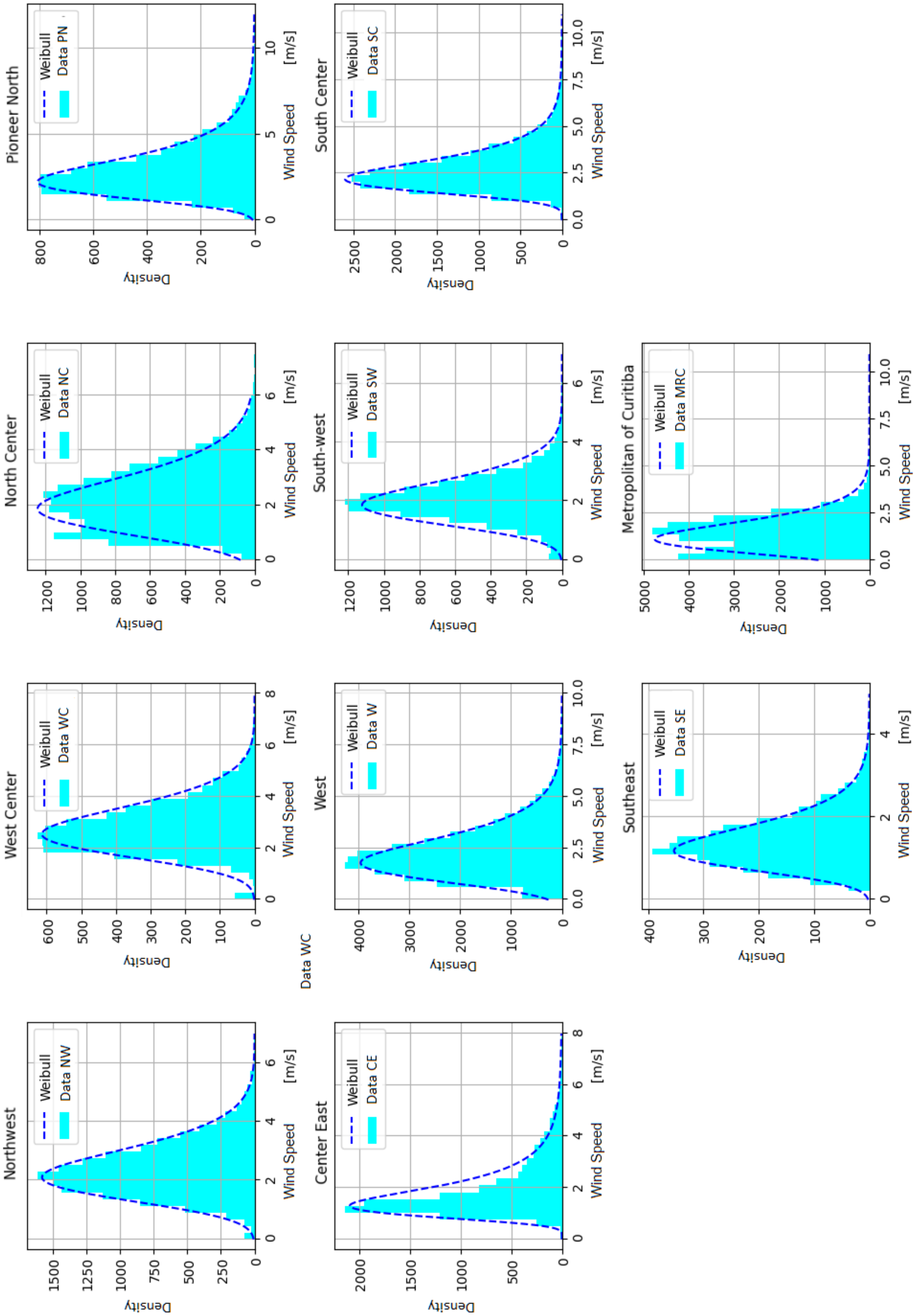

Figure 4. Histograms from the random simulations of the Weibull distribution of the average sustained wind, v in m, for all mesoregions of the State of Paraná

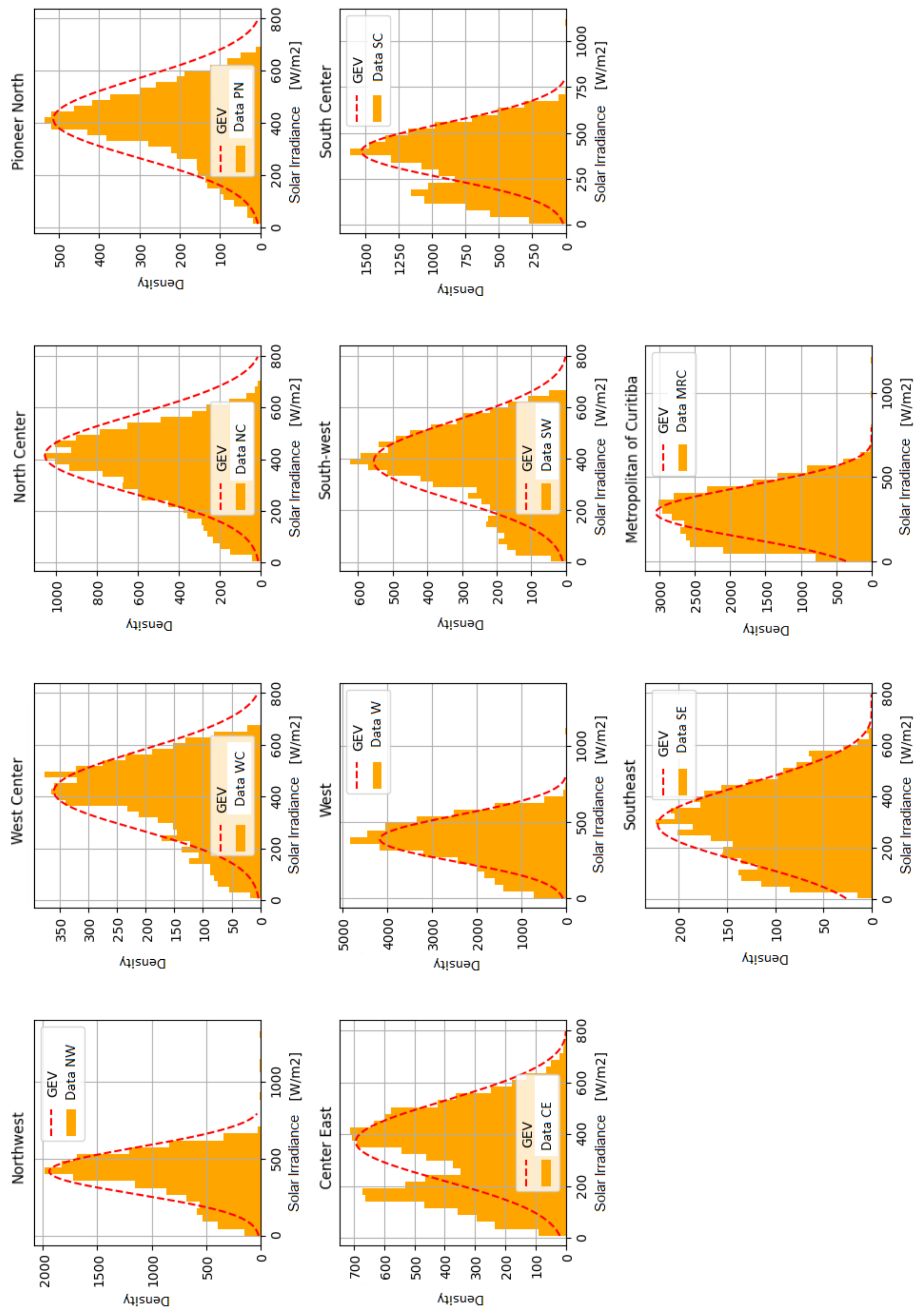

Figure 5. Histograms from the random simulations of Generalized Extreme Values Distribution (GEV) for solar irradiance, I_{solar} in kWh/m^2, for all mesoregions of the State of Paraná

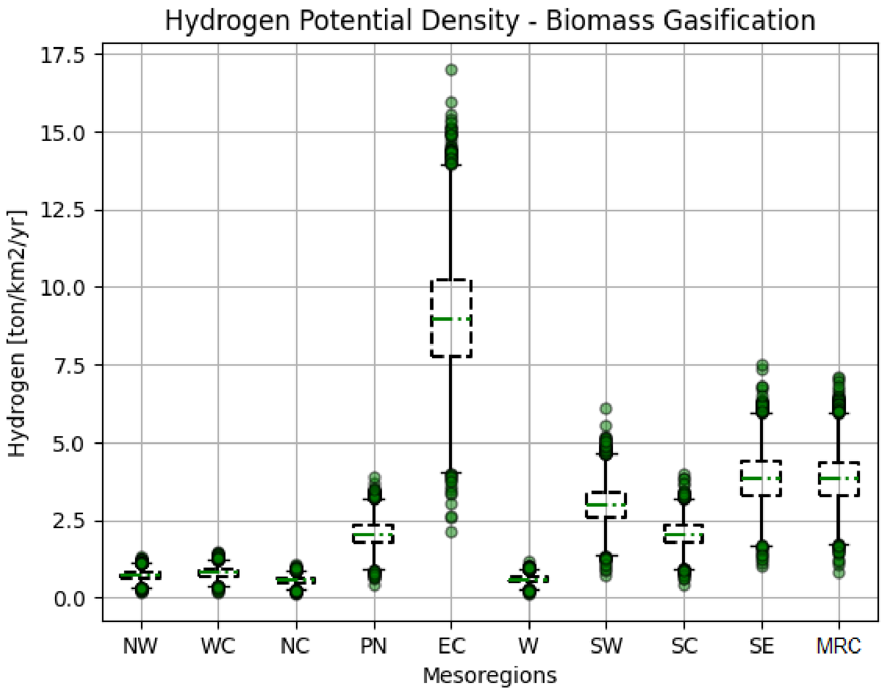

Figure 6. Projections for annual hydrogen (H_2) production theoretical potential density via residual solid biomass from agriculture and planted forests via DFB gasification by mesoregions of the State of Paraná, Brazil (tonH_2/km^2/year).

In lower scales, there are significant potentials in the mesoregions of the southwest (SW), with 3.016, the southcenter (SC) with 2.069, the southeast (SH) with 3.869, and even the metropolitan region of the state capital Curitiba (MRC), with 3.858, all in tonH_2/km^2/year.

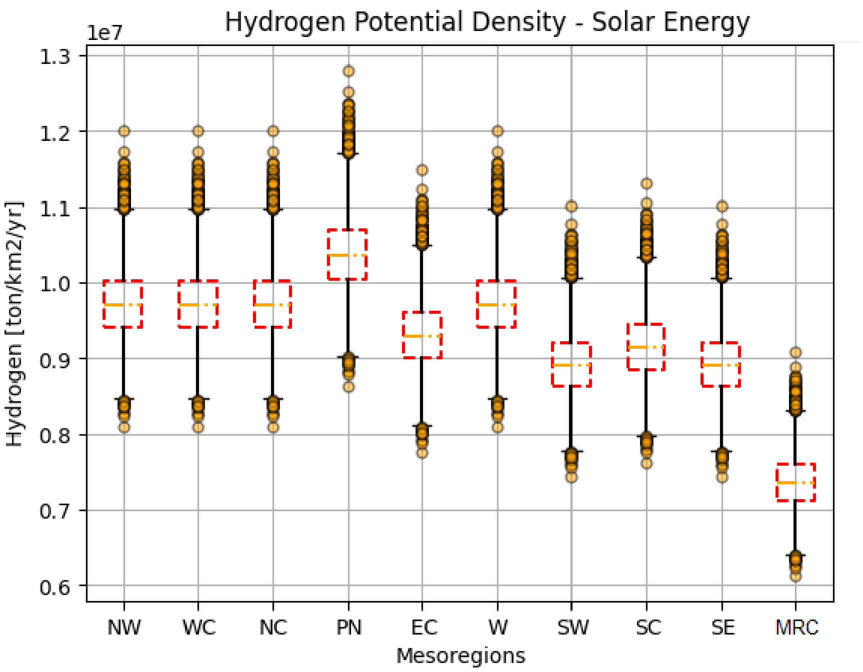

Figure 7. Projections for annual hydrogen (H_2) production potential density from solar energy, via electrolyzers, by mesoregions of the State of Paraná, Brazil (tonH_2/km^2/year).

Figure 7 shows the greatest potential of hydrogen production is in the mesoregion of Pioneer North (PN), with an average of 10,384,502.42 tonH_2/km^2/year, with a 95 confidence interval e between 9,089,855.703 and 11,434,600.041. The mean potentials among all the regions are close, except for the metropolitan region of Curitiba (MRC) since there would be less available area for PV plants.

3.3 Hydrogen Production Potential: Wind Energy

The density of the annual hydrogen (H_2) theoretical production potential from wind energy, via electrolyzers, by mesoregions of the State of Paraná, Brazil was computed by Eqs. (3) and (4), with the data from Table 2, and from the simulations of the electrolyzer production rate in kWh/kgH_2 of Fig. 2, which is the same used for the solar energy, and of the sustained velocity shown in Fig. 4. The results are presented in Fig. 8.

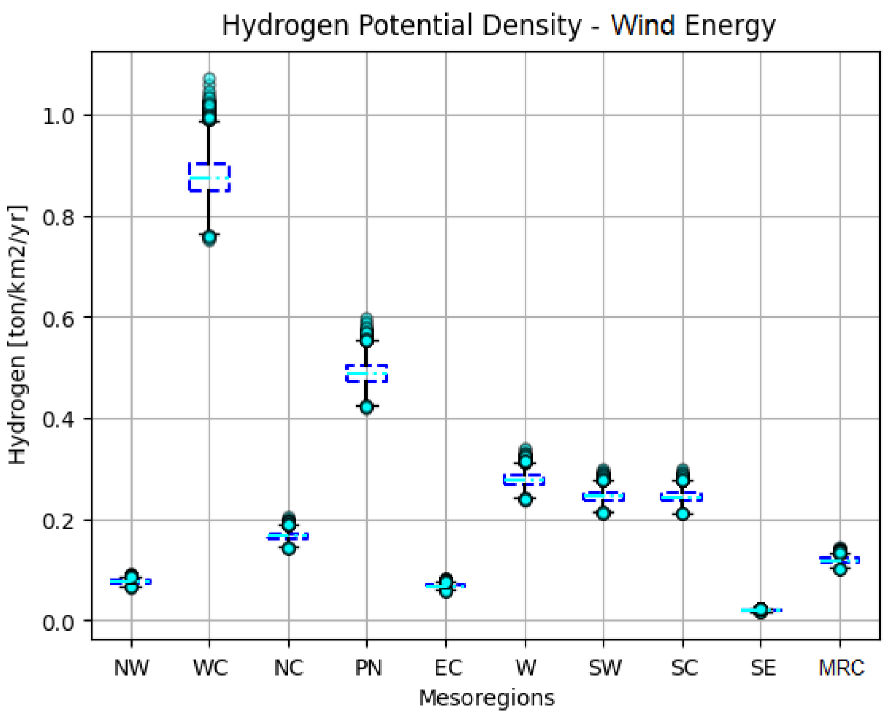

Figure 8. Projections for annual hydrogen (H_2) production potential density from wind energy, via electrolyzers, by mesoregions of the State of Paraná, Brazil (tonH_2/km^2/year).

In the pathway from wind energy, the mesoregion in the State of Paraná that presented the greatest potential of the theoretical production potential of hydrogen is the Center-West (CO), with an average of 0.889 tonH_2/km^2/year, with a confidence interval of 0.857 e 0.921. One of the reasons for such disparities is that the meteorological stations located there present higher averages of sustained wind (SIMEPAR). The mesoregion "norte pioneiro" (NP) may also be a potential region for hydrogen production with half of the CO mesoregion potential.

3.4 Overall Theoretical Hydrogen Production Potential in the State of Paraná

The overall theoretical hydrogen production potential in the State of Paraná is summarized in Table 3, where one finds the average of each pathway and the respective energy equivalent considering the LHV of the hydrogen as 120 MJ/Kg. The solar pathway is clearly superior to the others with 93.029 $\times 10^6$ tonH_2/Km^2/year; orders of magnitude superior. The area considered for PV plants and hydrogen generation plants are all the urbanized areas of the state. The theoretical potential from biomass residue is also significant, at least when one compares with other Brazilian states, since Paraná is the second largest producer of agriculture and forest crops IBGE (2023).

Table 3. Overall projections for annual hydrogen (H_2) production potential density from residual biomass, solar and wind energy for the State of Paraná, Brazil (tonH_2/km^2/year)

Pathway	H_2 (ton/Km²/year)	MJ/Km²/year	Kcal/Km²/ano	toe/Km²/year
Residual Biomass - Gasification	26.647	3.20×10^6	7.65×10^8	7.65×10^4
Solar - Electrolysis	93.029×10^6	1.12×10^{13}	2.67×10^{15}	2.67×10^{11}
Eolic - Electrolysis	4.67	5.61×10^5	1.34×10^8	1.34×10^4

4. CONCLUSIONS

This paper presented the theoretical potential of hydrogen production in the State of Paraná by the pathways of solar and wind energy with electrolyzer, and from agriculture and forest residues biomass gasified in dual bed fluidized gasifiers (DFB). The potentials were expressed in tonH_2/km^2/year and for energy equivalent considering the low heating value of the H_2. The calculations considered the agriculture yield from 2022/2023, the solar and the wind atlas from the literature and from public records. Uncertainty analysis was carried out by the Monte Carlo method and shows the likelihood of ranges for future reference.

The results of the simulations showed that there is a great potential density for "solar hydrogen", while for the eolic pathway, it is not promising as it is in today's Paraná. Hydrogen from biomass residues may be interesting since the conversion is "mass-to-mass" and it would take only the residues.

The results and conclusions are limited to the assumptions adopted in the work. While, at this point, it may be used to design policies to foster hydrogen as an energy carrier for the energy transition, further considerations of the peculiarities of the terrain, also require economic and environmental assessments of feasibility since the overall goal is the sustainability as a whole.

5. ACKNOWLEDGEMENTS

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