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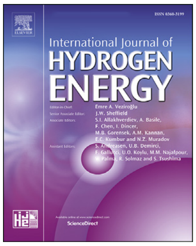

Residual biomass-based hydrogen production: Potential and possible uses in Ecuador

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HIGHLIGHTS

- The H2 potential based on residual biomass of Ecuador is calculated.
- The gasification-based path appears as the most promising alternative for H_2 production, in terms of scale and yield.
- The H_2 potential could cover the demand of this input in three of the analysed economy sectors.
- The projected H_2 availability makes it attractive for chemical and petrochemical applications in Ecuador.
- The fulfilment of the H_2 potential estimation of Ecuador is reached in this paper.

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ABSTRACT

The residual biomass sources available in Ecuador are evaluated as prime matter for hydrogen (H_2) production when considering that it sourced in agriculture, animal husbandry and forestry-related activities. The analysis is performed out of the official cropping information available per provinces. H_2 production methods to be assayed consider thermochemical, biochemical and electrochemical paths. The total H_2 production potential is 1,600,000 ton H_2/year and its use as energy vector would contribute with 38% of the national energy demand in 2017. In addition, its potential application as input in fat hydrogenation and nitrogenated products, in a country-wide scale, would be completely fulfilled. This finding demonstrates that residual biomass-based H_2 could become a suitable source of this vector for energy and chemical uses in Ecuador, since it proposes novel approaches for diversifying the secondary energy sources, petrochemical and chemical industry inputs with the purpose of promoting the incorporation of the country to the Hydrogen Economy.

Introduction

The residual biomass obtained from agriculture, cattle husbandry and forestry has gained interest as hydrogen source for energy-related and manufacturing-related chemical processes such as oil refining, fertilizers production, edible fat hydrogenation and related. This is because residual biomass offers advantages related to its availability, geographical

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distribution, environmental benefits and suitability for H_2 transformation [1]. However, every non-fossil-related H_2 production path requires a primary estimation of the residual biomass availability and the theoretical H_2 amount that could be obtained when a given conversion process is applied to it [2].

In such a context, the H_2 potential estimation gains relevance in order to assess residual biomass as starting point. In the United States of America, for instance, the potential H_2 production has been quantified out of renewable resources such as biomass. In such a case, agriculture residues, forestry residues, municipal solid waste (MSW) and energy crops have been assessed as feedstock for thermal H_2 generation technologies as gasification and steam reforming are [2]. The estimation reached a county-scale scope, and results were presented as H_2 potential maps. Regarding suitable end-use applications, a scenario of gasoline substitution in transportation was proposed and reached successful replacement outcomes in most of the counties. Authors also emphasise in the current barriers and constrains related to H_2 penetration in sustainable mobility [2]. Other related studies have incorporated constrains analysis and forecasting evaluations. Land-use restrictions have been recognised and assayed as relevant constrains for renewable resources-based H_2 generation. In addition, the use of H_2-powered vehicles with fuel cells as conversion technology has been forecasted up to 2050 [3]. Other related paths for H_2 production out of biomass link this end-use energy vector with the methane contained in biogas or landfill gas as intermediate reactant. The raw biomass sources were municipal effluents, manure, organic waste originates by commercial activities and landfills and all of them were assessed in anaerobic digestion-based processes. Authors also established a yield factor of 2.74 kg CH_4/kg H_2 for this path [5]. In this context, it is also relevant to mention that countries with a significant availability of residual biomass sources highlight it as the most suitable resource for ensuring a proper supply chain related to H_2 generation, when compared to other renewable resources. Amongst these cases Pakistan [6], Bangladesh [7] and Malasya [8] can be mentioned.

A similar assessment was carried out for Canada, yet it considered only biomass sources and an anaerobic-digestion based path. The feedstock included woody non-stem, wood product, agricultural crop residues, livestock manures and organic municipal waste residues [9]. The potential H_2 generation based in renewable resources has also been evaluated in Argentina. This was made in a province-scale scope and with no differentiation amongst renewable energy sources [10]. Besides these studies scoped in determined territories, the H_2 production based on residual biomass of the palm-oil processing industry has been proposed in a world-wide level. Authors affirmed that it is possible to fulfil 44% of the 2006 global H_2 demand with this renewable resource [11]. In Bangladesh, residual biomass is recognised as the most promising renewable source for H_2 production if aimed to fulfil the energy demand of the local residential sector [7]. It is reported that the total potential of residual biomass gathers agriculture, forestry and MSW and it is equivalent to 47.71 million ton/day of coal in terms of energy [7]. However, the theoretical amount of H_2 is not reported even if gasification is recognised as the most suitable technology for energy conversion. All these studies demonstrate a growing interest in linking the availability of renewable biomass-based resources with the potential H_2 production and its exploitation.

In addition, other H_2 production estimations that were based in renewable sources not related to biomass can be mentioned. In Algeria, for instance, the H_2 production potential was evaluated by considering an electrolysis-based path, powered by the solar and wind energy available in this country. In certain regions, annual H_2 production potential figures of 2.1×10^5 ton/year km^2 were reported. Also, it is pointed that the Algerian Sahara region is suitable for hosting large-scale H_2 production facilities, based in wind and solar power [2]. Other related study performed for Morocco showed a preliminary estimation of solar power-based H_2 production through electrolysis that also included H_2 potential maps. Results showed a total potential amount of 3.3×10^9 ton H_2/year whose production costs varied between 4.64 and 5.79 $/kg depending on the location The southern region showed the highest potential for H_2 production. This fact concorded the distribution of the solar irradiation and the related electricity production potential [12].

Other example that was evaluated in the Latin American region is the province of Cordoba, in Argentina. The wind power-based H_2 production potential and its possible coupling to transportation was evaluated. The H_2 production was estimated at 3.74×10^7 ton H_2/year for this case [13]. Further studies for the same province assessed financial figures for H_2 production and transportation. Also, the wind power estimation was performed with a larger accuracy and considering a specific wind farm. Results reported a cost 9.41 USD/kg H_2 for the described scenario [14]. In Venezuela, the electrolytic H_2 potential has been evaluated based on solar PV, wind and hydro (mini hydro scale) with a H_2 production of 2.073×10^4 ton/year. The H_2 obtained widely cover the energy needs of rural areas of around 828,000 inhabitants [15].

In Iran, an estimation of the H_2 production potential was performed by adopting a electrolysis-based scenario that was combined to the exploitation of the geothermal resources available along the 14 provinces of this country. The geothermal resource-based electricity was evaluated for each one of the provinces and a total electricity generation potential of 4.34×10^6 GWh/year was reported. Even if the total and individual H_2 potential were not reported in this work, the provinces with the largest H_2 performance index were identified by applying decision making modelling [16].

Finally, in Ecuador (the study case of this work), the H_2 production potential of several renewable energy sources and municipal solid waste (MSW) has been assessed [17–19]. For instance, a province-scale assessment that was coupled to transportation diesel fuel replacement has been reported [19]. Results showed that it is possible to fulfil the energy demand of urban public transportation in 91% of the territory with MSW-derived H_2. However, residual biomass obtained from agriculture, cattle husbandry and forestry has not been yet evaluated as primary energy source for a H_2 production potential study. For this reason, the H_2 production based on residual biomass in Ecuador is evaluated in this paper. In addition, the H_2 production distribution was evaluated according to geographical considerations with the purpose of analysing a non-centralized H_2

production scenario. This analysis is based on the official information of waste biomass generation in each one of the Ecuadorian provinces [20]. Moreover, the methodology reported in Ref. [18] is also adopted for this study. In such a context, H_2 production and H_2 production density are calculated per waste biomass type and province.

The relevance of this last indicator can be justified according to the following statements: 1. It indicates the H_2 production potential of a single region in terms of its terrain area instead of absolute values. This consideration allows displaying the distributed nature of the H_2 production proposal according to the residual biomass location, and in the same manner that has been adopted for other renewable sources (such as wind or solar energy) in similar estimations. 2. It enables comparing the results obtained in this work with the figures reported for other territories in studies that also adopted this intensive indicator for presenting the potential of a single energy resource, in a given territory. Adopting similar indicators is expected to expos the suitability for comparing and establishing a relative suitability through the results and further studies. 3. Its use in H_2 production potential assessments is common and widely accepted which is convenient for further comparison purposes. Hence, these indicators are reported as the result of the H_2 production assessment stage.

The second stage of this research sequence aims to identify potential end-use applications for the residual biomass hydrogen. For this purpose, the local fulfilment of primary energy demand and the H_2 demand of locally identified stakeholders such as an oil refining processes, potential nitrogenated compound production and fat hydrogenation are considered. The estimation of local demand rates expects to establish specific links between local sources and consumers of waste biomass-based H_2. The information presented in this paper expects to complete the assessment of renewable sources-based H_2 production in Ecuador [17–19]. These results aim to become a contribution to the core information of further analysis related to the identification and subsequent development of local exploitation proposals of H_2 and their incorporation in the local economy.

Waste biomass potential in Ecuador

One of the primary information sources that were adopted for this research is the Bioenergy Atlas of Ecuador [20] which presents geolocation-related information for the main crops and cattle nursing facilities along the country. Regarding the residual agriculture biomass types, the main ten products were selected in order to determine the amount of waste biomass generated during their production cycle: rice, banana, cocoa, coffee, sugarcane, maize, palm oil, plantain, pineapple, and palm heart. These crops were selected since they share 84% of the total national agriculture production in Ecuador. In addition, these crops are linked to the generation of 79% of the total residual biomass generated by permanent and seasonal cropping in Ecuador [20].

In addition, cattle husbandry waste was sorted by source (poultry, beef and pork cattle). The registered forestry waste information included in Ref. [20] was gathered from registered plantations in order to be included in the database. Using this information source ensures the analysis is based in a proper dataset.

Table 1 summarises the waste biomass amounts considered for this research in each one of the provinces of Ecuador. It should be mentioned that information included in Table 1 intentionally skips non-significant amounts of waste biomass in certain provinces and reports its values as null. This consideration is adopted since a minimum biomass amount for feasible exploitation has been already reported. This minimum biomass amount can be expressed in energy terms as 4.5 TJ/year (4000 MWh/year) [20].

Residual biomass-based H_2 production

Biomass-to-H_2 conversion methods can be sorted by the nature of the feedstock and the related energy conversion technologies [8]. The direct conversion paths are related to thermochemical and biochemical processes, while indirect H_2 generation paths include combination of combustion and electrolysis [6]. Regarding the thermochemical paths, gasification and pyrolysis can be considered amongst the available alternatives. In the case of biochemical methods, anaerobic digestion has been recognised as a suitable alternative that combines energy-related efficiency and positive environmental impact, even if it needs to overcome several challenges related to its economic feasibility. These challenges are mainly associated to the estimation of the cost/benefit ratio for this conversion process. Furthermore, external factors such as pre-treatment alternatives for biomass and the effect of operational conditions should be included in further estimations [21]. These factors have not been extensively assayed in the H_2 production potential estimation, hence these fields are recognised as research topics under development.

Regarding electrolysis, it is recognised as mature technology that is also widely applied [8]. However, its energy requirements are relatively large, and it only becomes feasible when electricity tariffs are low-priced [17]. In this study, three H_2 production methods are considered. The first one considers gasification purely; the second case combined combustion and electrolysis and the third one considers anaerobic digestion of biomass for obtaining biogas, plus gas conditioning, biomethane production and biomethane reforming as the last stage.

Regarding the third H_2 production method, it should be mentioned that the life cycle assessment (LCA) approach was adopted for comparing eight H_2 generation alternatives for analysis fossil fuels and renewable sources under the same conditions. Results indicated that biomethane reforming coupled to anaerobic digestion of cattle manure is the one with the lowest environmental impact amongst the assayed alternatives [22]. In addition, results obtained out of a pilot-scale H_2 production and distribution assessment proved that this path is one of the three most promising biomass-to-H_2 conversion technologies. The reported total costs were 4 euros/kg H_2, considering all the stages between production and final distribution in H_2 supply facilities. This figure is in a similar range when compared to the gasification-based path [23]. Finally, a study related to the US case for estimating the H_2 amount that can be obtained from biogas by reforming also remarked the suitability of this alternative [5]. These arguments support the selection of biomethane reforming as one of the H_2 production alternatives to be included in this study.

Gasification path

Regarding the gasification alternative, it is mentioned that the process is recognised for its economic feasibility, environmental compatibility and its H_2 yield. Besides these characteristics, it has also been associated to suitability for large-scale operation in cases that offer feedstock availability and inexpensiveness [24]. This H_2 production path has been assayed for lignocellulosic biomass mainly; moreover, the typical reported conversion yield that can be considered is 0.075 kg H_2/kg biomass dry-basis [3,10]. This figure was adopted in this study with the purpose of calculating the potential amount of H_2 that can be obtained from forestry and agriculture residues.

Combustion + electrolysis path

In this case, the considered H_2 production path is formed by two stages. The first stage is based on combustion since it is required during the thermal power generation (electricity). The second stage considers H_2 generation through water electrolysis powered by the electricity previously mentioned. For this calculation, the total amount of residual biomass that was identified is considered. This path was considered amongst the most relevant biomass-to-H_2 technologies in Ref. [23] since it is recognised as a sustainable and environmentally friendly alternative when compared to biomass firing.

Electricity generation

Electrical power calculation was performed by using a power conversion factor of 19.91% since it considered a steam cycle as energy conversion mechanism [12]. Equation (1) was used for the power estimation for each one of the provinces, and according to the individual biomass availability. The yield factors were adopted from Ref. [20], and results are presented in Table 2.

$$E_{EE} = (M_R \, PCI \, F_C) \, / \, R_{GP} \tag{1}$$

where, E_{EE} = Electrical power generated (MWh/year), M_R = Residual biomass amount (t), PCI = Net heating value for residual biomass (kcal/t), F_C = Conversion factor (kcal/kwh), R_{GP} = Power conversion factor.

H_2 production

The calculation of the amount of H_2 that could be obtained through electrochemical path considers an energy conversion factor of 75% of the high heating value (HHV) of H_2. In addition, an annual availability factor of the electrolysis facility was fixed in 95% [17]. The calculation model is shown in Equation (2).

$$P_{H2} = E_{EE} \, EFI \, F_D / HHV \tag{2}$$

where: P_{H2}: H_2 production (kg/year), E_{EE}: Electrical power generation potential, per province (kWh/year), EFI: Energy conversion efficiency (%), F_D: Availability factor (%), HHV H_2 = 39.4 kWh/kg.

Anaerobic digestion + biomethane reforming path

Poultry and cattle manure are the biomass types considered for assessing the anaerobic digestion-based path that is proposed in this study.

The H_2 production path, in this case, considers the following stages:

Table 1 – Waste biomass availability in Ecuador per location and activity.

Province	Agriculture residues (ton/year)	Cattle manure (ton/year)	Forestry residues (ton/year)	Total residues (ton/year)	Residues location density (ton/km^2/year)
Azuay	7010	104,101	0	111,112	13
Bolívar	80,682	40,633	0	121,315	37
Cañar	237,177	54,692	0	291,869	75
Carchi	3639	47,724	0	51,364	14
Chimborazo	65,962	74,045	0	80,642	15
Cotopaxi	175,573	81,561	36,404	293,539	45
El Oro	1,542,216	36,191	0	1,578,407	264
Esmeraldas	4,267,607	26,425	9638	4,303,671	289
Guayas	4,094,557	173,215	19,949	4,287,721	250
Imbabura	46,806	33,598	50,123	130,528	28
Loja	227,017	48,353	0	275,371	25
Los Ríos	4,340,758	20,786	45,146	4,406,691	705
Manabí	587,761	186,878	4875	779,515	42
Morona S.	27,742	21,184	0	48,926	2
Napo	25,749	8148	0	33,898	3
Orellana	402,699	7203	0	409,902	20
Pastaza	15,352	26,361	0	41,713	1
Pichincha	772,813	178,886	28,931	980,630	103
Sta. Elena	6118	8130	0	14,249	4
Sto. Domingo	659,749	102,608	21,088	783,446	187
Sucumbíos	48,314	7004	0	55,318	3
Tungurahua	0	130,182	0	130,182	39
Zamora	27,429	21,502	0	48,932	5
TOTAL	**17,603,374**	**1,439,420**	**216,157**	**19,258,952**	**77**

Table 2 – Electrical power generation potential, per province in Ecuador– Steam cycle path.

Province	Electrical power generation (MWh/year)
Azuay	7010
Bolívar	80,682
Cañar	237,177
Carchi	3639
Chimborazo	65,962
Cotopaxi	175,573
El Oro	1,542,216
Esmeraldas	4,267,607
Guayas	4,094,557
Imbabura	46,806
Loja	227,017
Los Ríos	4,340,758
Manabí	587,761
Morona S.	27,742
Napo	25,749
Orellana	402,699
Pastaza	15,352
Pichincha	772,813
Sta. Elena	6118
Sto. Domingo	659,749
Sucumbíos	48,314
Tungurahua	3840
Zamora	27,429
TOTAL	**17,603,374**

a. Biogas generation through anaerobic digestion: the calculation requires the volatile carbon content of residues and a methane conversion factor (0.2) that is based on the maximum methane emission of them. This estimation considers common climate conditions in Ecuador [20].
b. Biomethane concentration: this calculation considers that the biomethane yield is the 87% of the initial methane amount that is contained in biogas
c. H_2 production through biomethane reforming: A conversion factor of 0.30 kg H_2/kg biomethane is adopted for this calculation [5]. This figure represents 85% of the stochiometric conversion of biomethane reforming.

Results and discussion

According to the calculation conditions, the total amount of H_2 that was calculated is approximately 1,600,000 ton/year which includes the single contribution of each one of the conversion paths mentioned in Fig. 1. These figures show that gasification is the process that contributes the most to the H_2 generation amongst the production paths that were analysed. This finding can be justified due to the proportion of agriculture residues and the suitability of gasification as thermochemical H_2 production path.

The geographical distribution of H_2 generation through gasification and its production density are shown in Figs. 2 and 3. It can be notice that the provinces located in the shore region have the most relevant potential in terms of H_2 production suitability.

The H_2 production estimation obtained for the remaining paths had a similar behaviour to the one shown by the gasification case. Results are shown in Table 3. Even if a feasibility study should select the most promising path for each geographical location, the main purpose is to present an overview of the overall potential of H_2 production. In addition, results show that three provinces (Esmeraldas, Guayas and Los Rios) could contribute with the 72% of the national potential.

The H_2 production potential results are shown in Table 4 for comparison purposes. Figures reported in the part 1 of this study are also included for comparison purposes. Considering scale issues when comparing the results to the potential figures reported for other countries, it can be affirmed that Ecuador offers promising results for the potential use of H_2 as energy vector and raw material for chemical processes.

End-use proposals for H_2

The produced H_2 can also be used as energy vector or input in manufacturing/oil refining processes.

Energy vector

In this scenario, the H_2 potential availability generated through the gasification path could fulfil 38% of the total energy consumption in 2017 for Ecuador [25]. The differentiated consumption of fuels, primary energy sources and secondary energy sources per sector is presented in Table 5. Results show that the energy demand of fuels in industrial, residential and commercial sector could be covered by residual biomass-derived H_2.

Prime matter for chemical processes

Besides potential energy-related uses for the projected amount of H_2, a scenario that considers suitable applications in other chemical processes was also assessed.

Oil refining

Regarding the oil refining/manufacturing use proposal, the H_2 demand of diesel and heavy naphtha hydrotreating processes (HDS and HDT, correspondingly) of the Esmeraldas Refinery is considered. For both processes, the annual demand is 8341 ton/year, assuming a continuous operation of 8000 h [26]. This amount would require 2.5% of the total H_2 potential of the province of Esmeraldas, in the gasification scenario. Hence, a more detailed analysis is required in this potential application.

Fat hydrogenation

One of the mature technological applications in the Ecuadorian industrial sector is the fat hydrogenation process which is mainly related to the alimentary sector. Vegetable fat and oil industry plays a significant role in the local economy. According to Corporación Financiera Nacional (CFN), palm tree, coconut, almond, jojoba, sunflower, soy, olive and turnip are the main sources for the vegetable oil produced in Ecuador, being palm oil the most significant [27].

Furthermore, it should be mentioned that the main products are raw palm oil, refined palm oil, raw kernel oil, edible

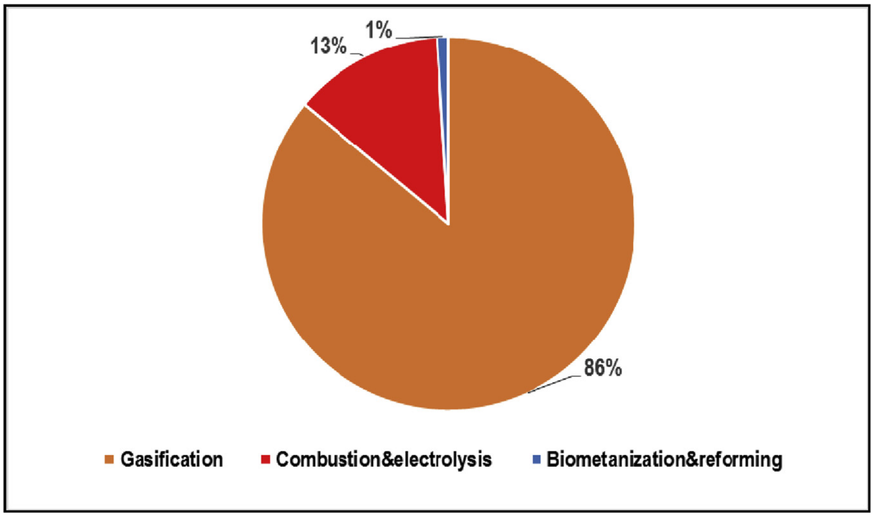


Fig. 1 – H_2 production share.

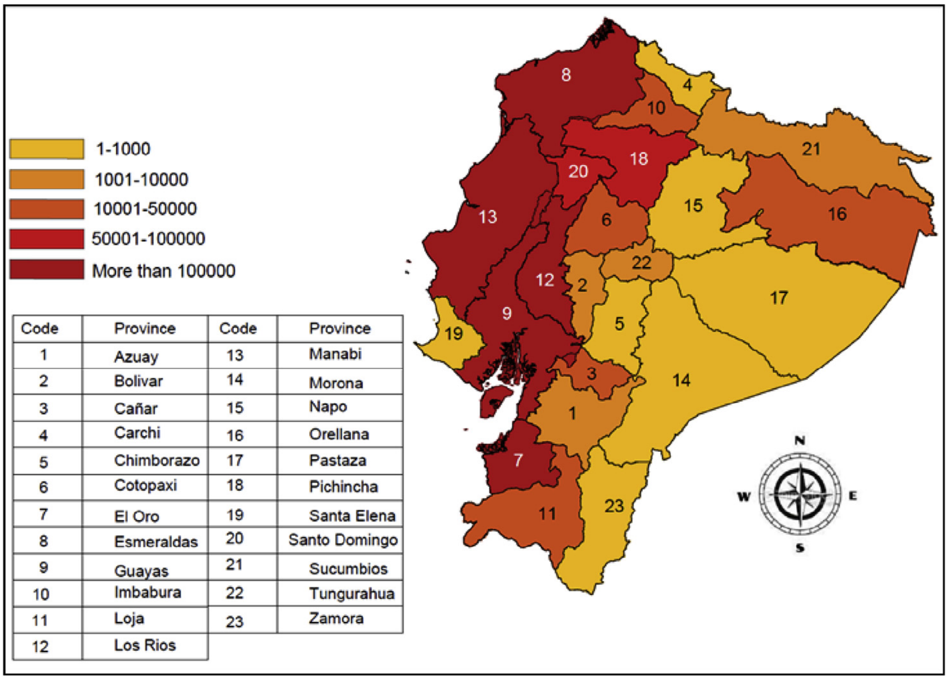
oil, palm olein, palm stearin, vegetable lard, biodiesel and soap. Concerning hydrogenated vegetable lard, it is mentioned that the total amount produced in Ecuador during 2016 was 84.398 kg, while the total amount in 2017 was 115.485 kg [28]. This growth represents an increase of 27% in the hydrogenated products demand.

In order to reduce the iodine index of a fatty input to 100 g iodine/g oil, the theoretical amount of H_2 is 0.0795 kg H_2/t of oil or 0.883 STD m^3 H_2/t of oil. In addition, it is reported that the effective amount of H_2 used in this type of operations is 0.93 STD m^3 H_2/t of oil [29]. Regarding its production process, it should be mentioned that it usually requires a nickel-based catalyst and concentrated H_2 (at least 99.8% v/v) [29]. The projected amount of H_2 that can be assimilated by this potential use is shown in Table 6.

Figures shown that the H_2 demand required for fat hydrogenation can be easily covered by MSW-based sources; moreover, this scenario is even suitable in any of the provinces analysed for this case. Hence, this use in the manufacturing sector can be coupled to any energy-related application.

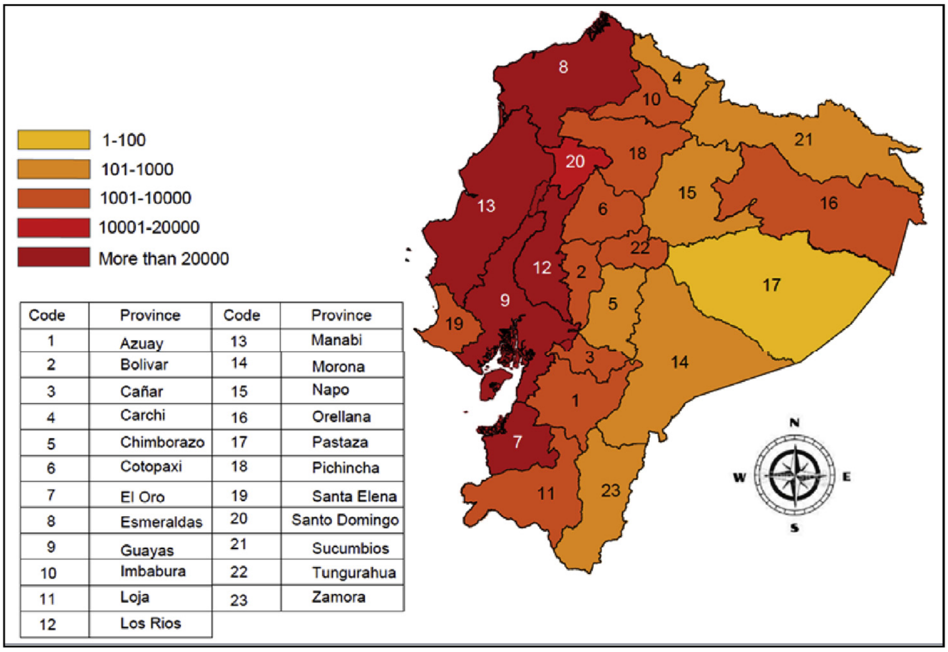
Nitrogenated products (ammonia and urea)

The use of petrochemical fertilizers is a common practice in the Ecuadorian agriculture sector [28]. Even if there is not a current local production of nitrogenated substances in Ecuador, their



Code	Province	Code	Province
1	Azuay	13	Manabi
2	Bolivar	14	Morona
3	Cañar	15	Napo
4	Carchi	16	Orellana
5	Chimborazo	17	Pastaza
6	Cotopaxi	18	Pichincha
7	El Oro	19	Santa Elena
8	Esmeraldas	20	Santo Domingo
9	Guayas	21	Sucumbios
10	Imbabura	22	Tungurahua
11	Loja	23	Zamora
12	Los Rios		

Fig. 2 – H_2 production per province (ton/year) – Gasification.



Code	Province	Code	Province
1	Azuay	13	Manabi
2	Bolivar	14	Morona
3	Cañar	15	Napo
4	Carchi	16	Orellana
5	Chimborazo	17	Pastaza
6	Cotopaxi	18	Pichincha
7	El Oro	19	Santa Elena
8	Esmeraldas	20	Santo Domingo
9	Guayas	21	Sucumbios
10	Imbabura	22	Tungurahua
11	Loja	23	Zamora
12	Los Rios		

Fig. 3 – H_2 production density per province - Gasification (ton/year km^2).

demand is covered by imports. Urea is one of the most common fertilisers, and their annual imports reached FOB USD 129′509.961 in 2018 [30]. Ammonia, on the other hand, has a lower bulk demand when compared to fertilisers, and reached FOB USD 316.412 in imports, in 2018 [31].

Table 3 – H_2 production and H_2 production density of residual biomass in Ecuador.

Province	H_2 production (ton/year)	H_2 production density (ton/year/km^2)
Azuay	8.03E+02	9,65E-02
Bolívar	7.05E+03	1.79E+00
Cañar	2.16E+04	6.85E+00
Carchi	4.77E+02	1.26E-01
Chimborazo	7.75E+02	1.19E-01
Cotopaxi	1.91E+04	3.13E+00
El Oro	1.38E+05	2.40E+01
Esmeraldas	**3.83E+05**	2.43E+01
Guayas	**3.71E+05**	2.42E+01
Imbabura	9.40E+03	2.05E+00
Loja	2.11E+04	1.91E+00
Los Ríos	**3.91E+05**	5.43E+01
Manabí	5.23E+04	2.92E+00
Morona S.	2.47E+03	1.03E-01
Napo	2.22E+03	1.77E-01
Orellana	3.60E+04	1.66E+00
Pastaza	1.41E+03	4.77E-02
Pichincha	7.26E+04	7.61E+00
Sta. Elena	5.83E+02	1.58E-01
Sto. Domingo	6.16E+04	1.63E+01
Sucumbíos	4.12E+03	2.27E-01
Tungurahua	5.14E+02	1.52E-01
Zamora	2.40E+03	2.27E-01
TOTAL	**1.60E+06**	**6.49E+00**

Bold values correspond to the three largest production values of H_2.

In industrial processing of fertilizers, ammonia and urea are usually produced in parallel. The usual prime matter, in both cases, is methane since it offers carbon and H_2 sources while nitrogen is obtained from air [32]. The most common ammonia synthesis path is the Haber – Bosch process which requires elevated pressure and moderately high temperature conditions (100 bar and 275 °C) [32]. Regarding the urea synthesis case, the Stamicarbon CO_2 stripping process is the one selected for projecting the potential input demand. For producing one t of urea (NH_2CONH_2), 125 kg of H_2 are theoretically required. According to Ref. [23], a conversion of 76% can be assumed, and the actual H_2 requirement should be 164.5 kg H_2/t urea.

In this context, the suitability of producing urea in Ecuador according to the potential H_2 availability, shown in Table 7.

Table 4 – H_2 production and H_2 production density of residual biomass – figures of reported H2 assessments and Ecuador.

Territory	Residual biomass potential (MM ton/year)	H_2 Production (MM ton/year)	H_2 Production Density (ton/km^2)	Year
USA [3–5]	N/A	30.21	3.30	2007
	383	31.00	3.39	2013
	N/A	1.64	0.18	2014
Pakistan [6]	86	6.60	7.48	2018
Canada [9]	145	8.21	0.82	2007
Global [11]	184,6	26.00	N/A	2007
Current study	19,3	1.60	5.64	2019

Table 5 – H_2 potential participation in the energy demand fulfilment (2017).

Energy Consumption Sector (kboe)	Fuels to be replaced (PS: primary sources; SS: Secondary sources)	Fuel consumption sector (kboe)	H_2 coverage percentage (%)
Transport, (45,097)	SS: gasoline, diesel oil, fuel oil	43,870	77
Industry (12,852)	PS: natural gas,wood, cane bagasse SS: LPG, gasoline, diesel oil, fuel oil	6986	485
Residential sector (12,174)	PS: wood SS: LPG	7648	443
Commercial sector (7106)	SS: LPG, diesel oil, fuel oil	2895	1171

LPG: Liquefied petroleum gas.

Table 6 – Linear projection of H_2 demand for fat hydrogenation (linear growth).

Year	Projection of local hydrogenated fat production (ton)	Projected H_2 demand (STD m^3)	Projected H_2 demand (kg)
2016	84.40	78.49	6.42
2017	115.49	107.40	8.79
2018 (not official data available)	146.57	136.31	11.15
2019 (projection)	177.66	165.22	13.51
2020 (projection	208.75	194.13	15.88

Table 7 – Projected H_2 demand for urea production in Ecuador (linear growth).

Year	Urea demand (ton)	Projected H_2 demand (t)
2010	371,007	61,031
2011	405,289	66,670
2012	406,622	66,889
2013	360,522	59,306
2014	442,650	72,816
2015	426,774	70,204
2016	436,625	71,825
2017	446,477	73,446
2018	456,329	75,066

Parameters such as the carbon and infrastructure availability are not considered in this analysis. The calculation considers the reported urea import figures for the Ecuadorian case up to 2014 [33], and projections from 2015 to 2020.

H_2 requirements shown in Table 7 lead to consider that the amount of H_2 demanded for such a type of application could be covered in a national wide perspective. In addition, the Province of Guayas and its surrounding jurisdictions could be a proper location for a potential production facility, since it demonstrates to have a proper H_2 production density for enabling potential gathering and handling procedures for the prime matter.

Conclusion

The residual biomass in Ecuador shows a significant potential for H_2 production and its use in energy and manufacturing processes. In the first case, the gasification-based path has been recognised as the one with the largest potential amongst the analysed alternatives. This is because its relative simplicity when comparing each one of the stages in the proposed paths, and due to the waste valorisation implied in this proposal. In the second case, its use as input in synthesis processes can be recognised as a relevant alternative due to its import substitution potential. This analysis aims to complete the renewable H_2 production assessment in Ecuador and to open new insights for further studies related to its exploitation. In a wider sense, it is expected that such a type of studies contributes to the H_2 incorporation in the local economy and to the energy availability solutions in the near future.

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