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Use of Municipal Solid Waste (MSW)-Derived Hydrogen in Ecuador: Potential Applications for Urban Transportation

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Abstract

This paper performs an assessment of the potential energy-purposed H_2 production in Ecuador from municipal solid waste (MSW). Thermochemical and electrochemical paths are considered for MSW conversion. Ecuadorian provincial MSW distribution (2016 data) provides the base information for assessing and constructing maps of the theoretical H_2 production yield and its density per unit area. Additionally, the use of H_2 in fuel cell-propelled urban public transportation is proposed as an end-use consumer. Results show that it is possible to fulfil urban public transportation energy demand in 91% of the country with MSW-derived H_2; in fact, the three provinces that together generate 57% of the available MSW (Guayas, Pichincha, and Azuay) could satisfy their public transportation diesel fuel demand with MSW-derived hydrogen. In the case of these three provinces, H_2 generation could replace by 2.57 times (on average) the local urban transportation diesel fuel demand. Finally, a possible scenario for a non-conventional H_2 production path is shown, which could also represent a suitable MSW final disposal alternative with benefits to urban mobility.

Keywords Municipal solid waste · Thermochemical conversion · H_2 production · Sustainable transportation

Abbreviations

MSW	Municipal solid waste
H_2	Hydrogen
GHG	Green-house gases
WTE	Waste-to-energy
t/year	Tons per year
LPG	Liquefied petroleum gas
kBOE	Equivalent oil barrel × 10^3
MMBOE	Millions of equivalent oil barrels
MW	Watts × 10^6
TJ	10^{12} Joule × 10^{12}
MMbbl	Barrels × 10^6
$BBstdm^3$	Cubic decimeters standard × 10^6
Wh/m^2day	Watt-hour per square meter, per day
MWh/year	Watt-hour × 10^6 per year
LHV	Low heating value
HHV	High heating value
MJ/t	Joule × 10^6, per ton
STE	Spilled turbinable energy
GWSR	Gasification combined with steam reforming
GWE	Gasification combined with electrolysis
PV solar	Photo-voltaic solar energy

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Introduction

The sustained growth in municipal solid waste (MSW) generation caused by urban populations is putting pressure on the current final disposal methods and increasing costs. The issue is also recognised as a pollution source, since dump yards, landfilling, and incineration (common disposal methods in developing countries) can affect nearby water and air quality, and contribute to greenhouse gas (GHG) emissions. These factors, in turn, can affect the health and quality of life of those populations and ecosystems located in the vicinity of MSW handling and disposal centres [1]. It is estimated that the current situation will continue to worsen, since the 4.3 billion urban inhabitants projected by 2025 could generate around 2.2 billion tons of MSW per year—double the

2012 output [2]. Now recognised as a global problem; sustainable MSW disposal has attracted considerable attention, as governments, research centres, and environmental and non-governmental organisations search for permanent and practical solutions. In this context, using MSW as a primary energy source is an attractive alternative based on the concept of waste-to-energy (WTE), as described [3, 4] below.

Among possible energy vectors, hydrogen (H_2) stands out due to its advantageous energy properties and its suitability for application in various production sectors, and across a wide range of technologies [5]. To this end, the conversion of prime matter MSW into an H_2 energy vector could be achieved by thermochemical or biochemical processes. In the first case, gasification appears to be the most highly-developed process [6–11], especially considering the availability of commercial-scale technology able to effect this conversion in large volumes [12]. In the second case, anaerobic digestion [13–16] and dark fermentation [17–21] are attractive potential biochemical paths for H_2 generation.

Indepent of the technological means of MSW-to-H_2 production, the evaluation of any potential project based on this energy vector requires information about the estimated amount of H_2 obtainable over a specific period within a given geographical area. Such information, even if only preliminary, is required to assess the feasibility of any WTE project, or any other initiative aimed at supplying H_2 for a chemical or petrochemical application on an industrial scale. Nevertheless, a literature review of this H_2 production path found no data related to its theoretical yield. One of the few published assessments estimates the potential H_2 production from renewable energy sources in the United States. This research considered various sources of residual biomass, landfill gas, and municipal wastewater, but did not include MSW [22]. It bears mentioning that MSW is partially formed by matter that can be considered residual biomass or "bio-waste" (for example, kitchen scraps, yard waste, and even wood) [23]. Another study also performed in the United States considers biogas obtained from industrial biomass waste and municipal wastewater as prime matter for H_2 production, with a projected potential of 300,000 t/year; however this paper also omits MSW [24].

With respect to the case of Ecuador, in particular, it should be noted that the country is currently implementing a significant shift in its energy mix; increasing the share of renewable energy over a medium-term time horizon. Residual biomass plays an important role of this process, due to its significant potential energy output and its transformability into multiple energy vectors. The energy and storage characteristics of H_2 also make it an attractive choice for transportation applications, among other possible end uses.

Based on the literature review, it is evident that much work remains to be done on the subject of MSW-derived H_2 potential; a finding also noted in other studies reviewed [25, 26]. The current paper aims to contribute to this research niche, estimating the theoretical amount of H_2 obtainable from Ecuador's MSW. This research also analyses the specific case of replacing diesel fuel in urban transportation, using data organized by internal political regions. It should be mentioned that MSW gasification and related H_2 use in transportation have been previously assessed and compared against other waste management alternatives in the United States, thus, the possibility of effectively combining this source and end use has already been established in the literature [10]. Although other proposals include the use of obtained H_2 to synthesize alternate fuels, [27–29], the direct use of H_2 in fuel cells offers advantages in terms of the energy yield of the entire conversion process [30]. As such, the current work analyses the use of H_2 as a transportation energy vector directly, instead of considering it as a part of a fuel synthesis supply chain.

The authors hope that the results of this paper will contribute to the literature regarding MSW use in transportation, as well as serve as a starting point for further studies focused on the Ecuadorian provinces with the most significant potential for diesel fuel-to-H_2 replacement. To this end, the specific purpose of this work will be to create a preliminary technical overview to identify specific scenarios to be developed in future research and assessments.

Production, Consumption, and the Energy Potential of Ecuador

The Republic of Ecuador is located in the equatorial region of South America, with an estimated 2016 population of 16,500,000 inhabitants, of whom 64% live in urban areas [31]. The 2016 (base year 2015) key energy statistics for the country are shown in Figs. 1, 2, 3 and 4 and Table 1.

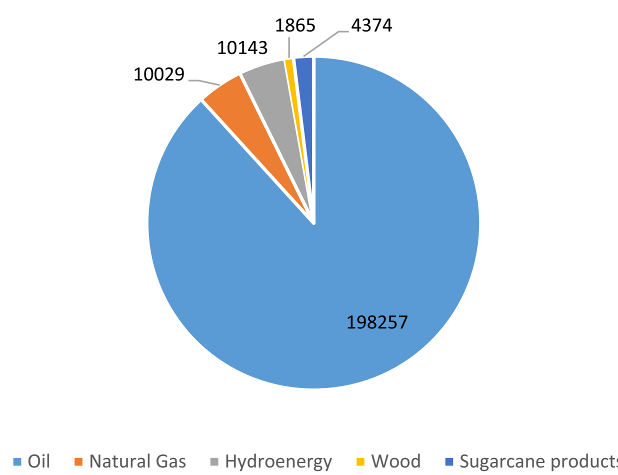

Fig. 1 Primary energy production in Ecuador, kBOE (2015) [32]

Table 1 Energy potential and primary source reserves of Ecuador

Renewable energy sources		Fossil energy sources 2015 [33]	
Source	Usable potential	Source	Proven reserves
Hydroelectricity (MW)	21,903 [34]	Oil, MMbb	8273
Wind power (MW)	1671 [34]	Natural gas, BBstdm^3	10.9
Geothermal energy (MW)	6500 [34]		
Biomass (TJ/year)	224,102 [35]		
Solar (Wh/m^{2}day)	4575 [34]		

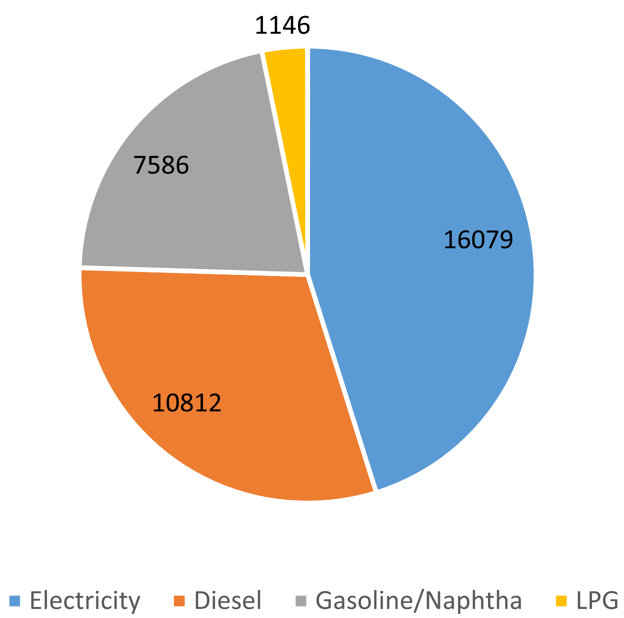

Fig. 2 Secondary energy production in Ecuador, kBOE (2015) [32]

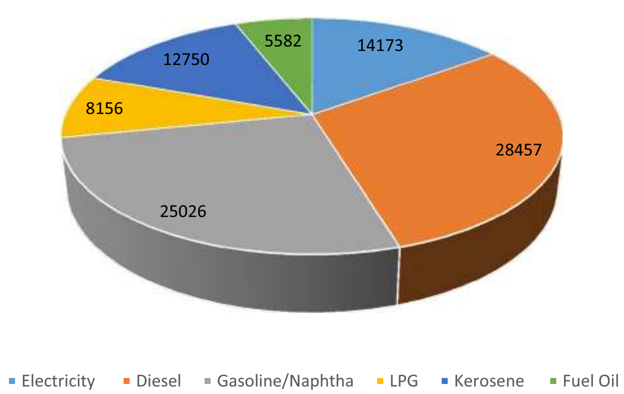

Fig. 3 Energy consumption per secondary source in Ecuador, kBOE (2015) [32]

Figures 1 and 2 illustrate production from primary and secondary energy sources, respectively. In Fig. 1, it can be seen that the country is overwhelmingly dependent on oil as its chief source of energy, while the balance of secondary energy sources (Fig. 2) is more evenly distributed.

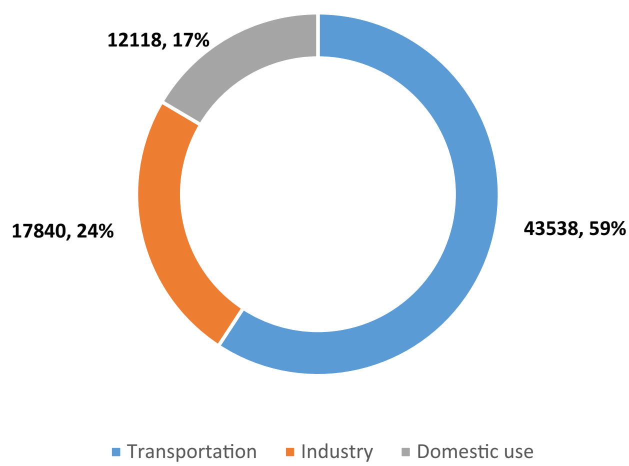

Fig. 4 Energy consumption per sector in Ecuador, kBOE (2015) [32]

On the consumption side (Figs. 3, 4), fossil fuels represent the energy source with the highest demand (85% of total), with transportation as the leading consumption sector in the country at 42% of the national energy consumption (101 MMBOE in 2014) [32]. Given that fossil fuel consumption vastly outstrips production, a national energy imbalance exists, in which some 50% of the fossil fuels required must be imported. Consequently, the development of local, renewable energy sources becomes highly desirable. The potential for such energy production is presented in Table 1. An efficient exploitation of renewable energy sources, especially biomass, could contribute greatly to reducing the nation's dependence on foreign imports and enhancing national energy security (Table 2).

Bioenergy Potential in Ecuador

Ecuador's potential biomass energy production has been assessed in several studies, with a primary focus on residual biomass [35–42]. The Bioenergy Atlas of Ecuador [37] represents the most extensive information source available on the topic, and contains a wide variety of data upon biomass waste from agriculture, animal husbandry, and forestry sources. The atlas [37] is organized into maps of energy

Table 2 MSW composition and energy content [43]

Component	Content (wt%)	LHV (MJ/t)
Food waste	59.56 ± 14.59	17,830
Paper	6.19 ± 3.97	16,176
Cardboard	5.68 ± 3.53	16,176
Plastic	11.31 ± 6.39	34,018
Glass	3.29 ± 2.64	–
Metal	2.73 ± 2.68	–
Others	12.51 ± 12.49	–
Total	100.00	16,387

potential and energy potential density, delineated by province and canton (district). Nevertheless, it does not mention MSW potential or availability. A recent study [43] into Ecuador's MSW potential was carried out based on "official information for 2013", and found that the three provinces with the most significant MSW generation rates are Guayas (1,495,431.0 t/year), Pichincha (960,216.5 t/year), and Azuay (182,817.6 t/year); between them comprising some 57% of the total national MSW generation [43, 44]. It is relevant to add that the country's three largest urban centers are located in these jurisdictions [26], indicating a clear relationship between population and MSW generation. The same authors compare several WTE technologies that can be applied to MSW, highlighting gasification as the most promising in terms of potential power generation (18,467 MWh/year).

Other sources report WTE assessment results for smaller jurisdictions. The city of Quito, for instance, has been assessed by analysis of several energy conversion paths and technologies [45]. It bears mentioning that WTE conversion may not always be the best solution in every case. The Province of Chimborazo's waste management issue, for example, was the subject of a study which ultimately recommended composting rather than energy-related waste disposal methods [46].

In the current study, a distribution map (Fig. 5) was constructed prior to calculating the theoretical amount of H_2 that could be obtained (both by jurisdiction, as well as nationwide). The procedure used was similar to the one suggested in [38], and was based upon information from (Moncayo J. Personal communication, 2017).

A detailed characterization of Ecuador's overall MSW composition has yet to be carried out by local waste management actors, however, several sources do report characterization results for specific zones such as the Province of Chimborazo [47], whose "residual biomass" content is 64.78%. Consequently, the MSW composition proposed by [43] (average composition and LHV) was adopted as an operational assumption, and the calculation procedure proposed in [48] was adopted for estimating the H_2 production-related data. For calculation purposes, the composition figures were fixed, since additional relevant proximate analysis figures such as the Ecuadorian MSW humidity content are not yet available.

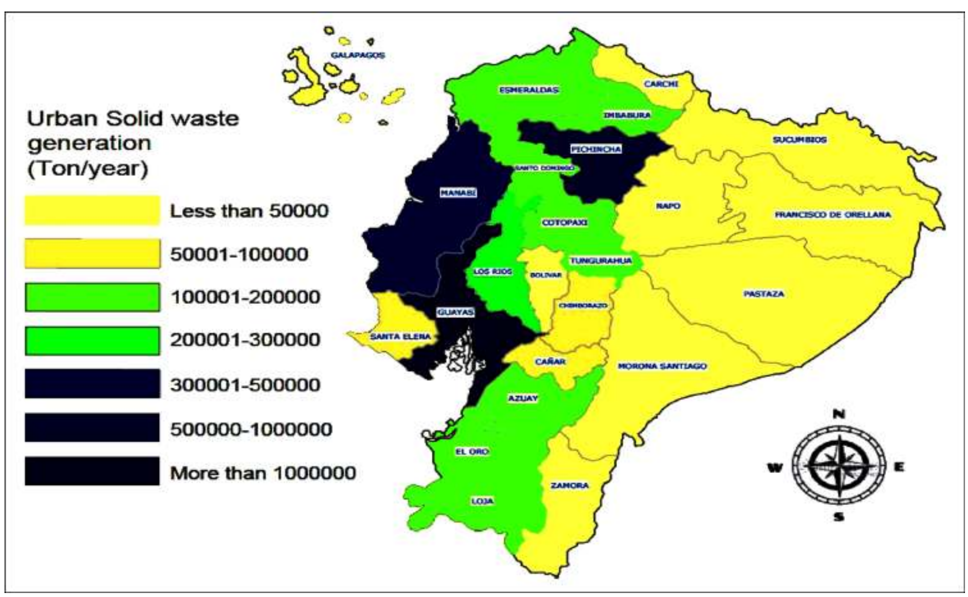

Fig. 5 MSW per province in Ecuador (2016)

Potential Renewable H_2 Production in Ecuador

Ecuador's renewably-sourced H_2 generation potential has been previously assessed in related studies [48, 49]. The first reference [48] proposes using spilled turbinable energy (STE) from hydroelectric plants powered by dams, and calculates that excess energy production at such facilities could have produced 1.25×10^4 tons of H_2 in 2013 through electrolysis. The second reference considered a broader scope, with solar photovoltaic energy, wind power, and geothermal power analysed for their potential to produce hydrogen to be used in transportation and rural electrification.

With respect to hydroelectric energy, it was reported that 65% of currently-imported gasoline could be replaced by H_2 produced through electrolysis [23]; a sufficient quantity to fulfil the demand of 9 of Ecuador's 23 provinces.

The second reference [49] calculated that the domestic cooking energy demand in rural areas could be satisfied in 20 of 23 provinces using renewable energy. Both references highlight the potential of H_2 as an energy vector, and mention the possibility of using H_2 storage to transfer excess energy produced in some regions to satisfy the energy deficits of others. Concerning the general case of biomass, or the specific case of MSW as the prime matter in an H_2 production process, no relevant existing literature could be found during the present study.

MSW-Derived H_2 Production

The MSW-derived H_2 generation paths are similar to those used for other types of residual biomass, specifically: (a) gasification combined with steam reforming (GWSR); and (b) gasification combined with electrolysis (GWE). The parameters used for calculations in the current study are shown in Table 3.

H_2 Production Through Gasification Combined with Steam Reforming (GWSR)

This method for obtaining H_2 from MSW is the most highly-developed, and could be profitable assuming low-cost biomass feedstock and/or environmental protection incentives [51]. In this research, the biodegradable fraction of MSW was estimated at 60% [43]. A value of 10% by weight was taken as the expected process yield from the total feed stream. This figure was derived from an average of reported conversion processes [12, 50]. The H_2 distribution map and the H_2 production density map are presented in Figs. 6 and 7, delineated along provincial lines.

H_2 Production Through Gasification Combined with Electrolysis (GWE)

In this method, the gasification output stream (syngas) is fed into an internal combustion engine-based generator, which in turn produces the electricity used by the electrolyser to produce H_2 [52]. Although this alternative entails greater energy consumption compared to GWSR, renewable energy could nevertheless represent 92% of the primary energy required for its operation [50]. The H_2 yield calculation is based on an efficiency of 29% for the MSW-to-electricity conversion process, and an average low heating value (LHV) of 16,387 MJ/ton for MSW [48]. With respect to the electrolysis stage, an efficiency of 75% [48] is assumed, with an H_2 high heating value (HHV) of 120 MJ/kg. The availability factor of the electrolysis unit is considered to be 95% [48]. The H_2 production and H_2 production density are shown in Figs. 8 and 9, respectively.

The theoretical national production of H_2 under the two proposed methods (GWSR and GWE) is 265,056 tons/year and 111,000 tons/year, respectively. It should be noted that the first alternative (GWSR) would achieve a more significant yield, since it involves fewer stages for energy conversion, and would thus incur lower losses than the GWE method. In addition, it can be seen that the provinces which host the most highly-populated areas present the most significant potential H_2 production density.

Prospect of H_2 Produced from MSW in Ecuador

This paper proposes the use of MSW-derived H_2 as an energy source for transportation; specifically, the replacement of diesel-fuelled buses by vehicles powered by H_2-fed

Table 3 Calculation parameters for establishing the MSW-derived H_2 potential

GWSR path [43]		GWE path	
MSW biodegradable fraction, F_{DB} (%)	60%	MSW-to-electricity conversion efficiency, E_{CE} [43]	29%
Thermochemical conversion yield, E_{CT} (%) [12, 50]	10 wt%	LHV MSW [43]	16,387 MJ
		Availability factor, F_D [48]	95%

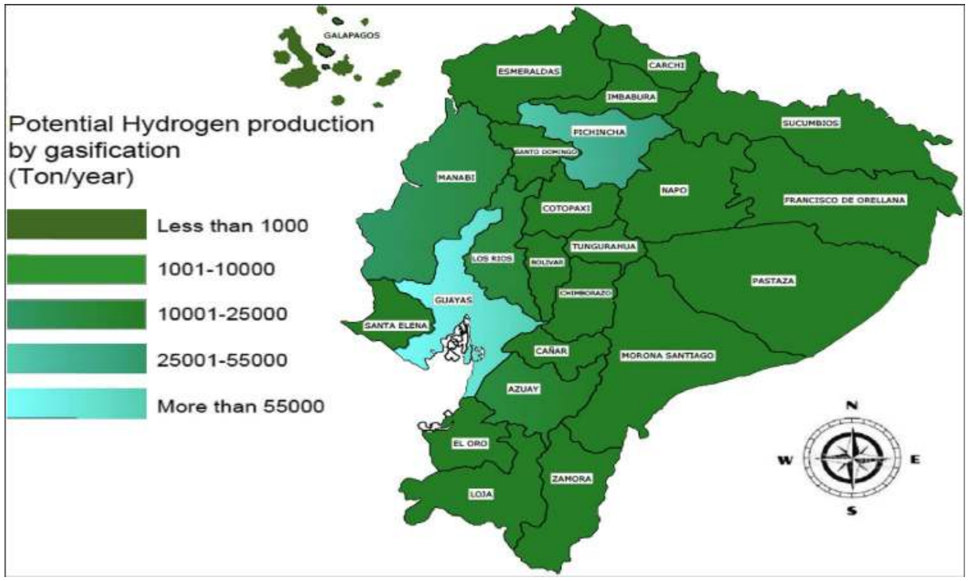

Fig. 6 Hydrogen production potential by GWSR (2016)

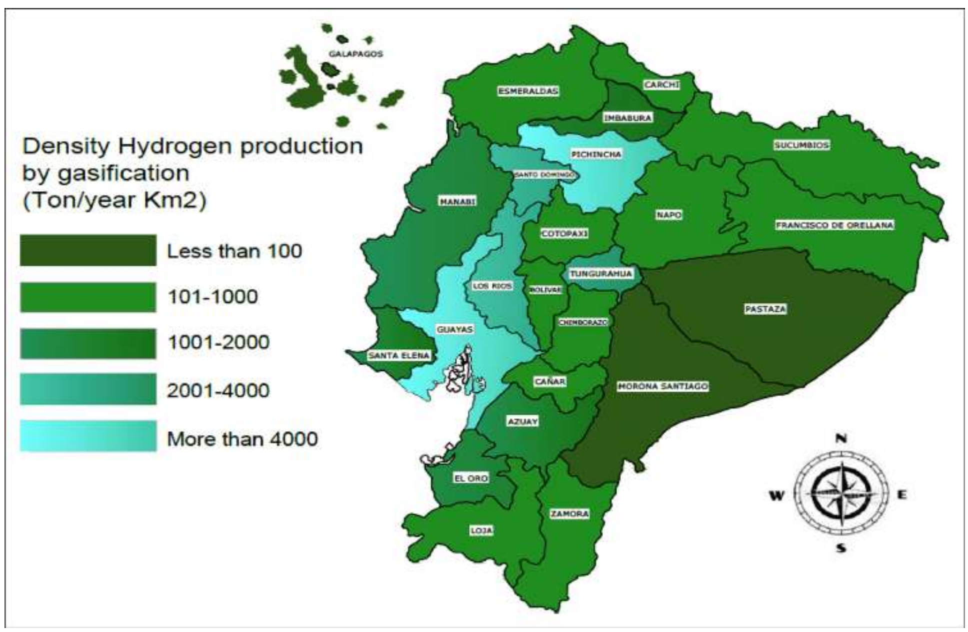

Fig. 7 Hydrogen production density potential by GWSR (2016)

fuel cells. This end use proposal has been previously analysed in other cities, but only for H_2 obtained from other production paths. For instance, electrolysis units running on solar PV and on-grid electricity have been proposed for Madrid [53]; electrolysis powered by excess hydroelectric energy for Asunción [54] and Cuenca [48]; and electrolysis powered by on-grid electricity for London [55]. These studies share a common goal of improving transportation sustainability, with a primary focus on the replacement of fossil fuel-based technology by more efficient alternatives such as H_2. Current research incorporates various facets of sustainability, for example, Cuenca, which is the third-largest Ecuadorian city and the only one recognized among the sustainable cities of the South American and Caribbean regions [56], nevertheless scores poorly in urban transportation. In this case, the main reason for this finding is the lack of public transportation, which is considered at length in [48].

This paper expands the scope of analysis of the urban transportation proposal to consider Ecuador at a national level, and presents as a novel proposition the use of MSW as a feedstock for H_2 production for this end use. Beyond improving the nation's sustainability indicators, additional potential benefits include a reduction in diesel fuel imports (48% of imported secondary energy) [27], and diversification of the national energy mix. This topic – along with its

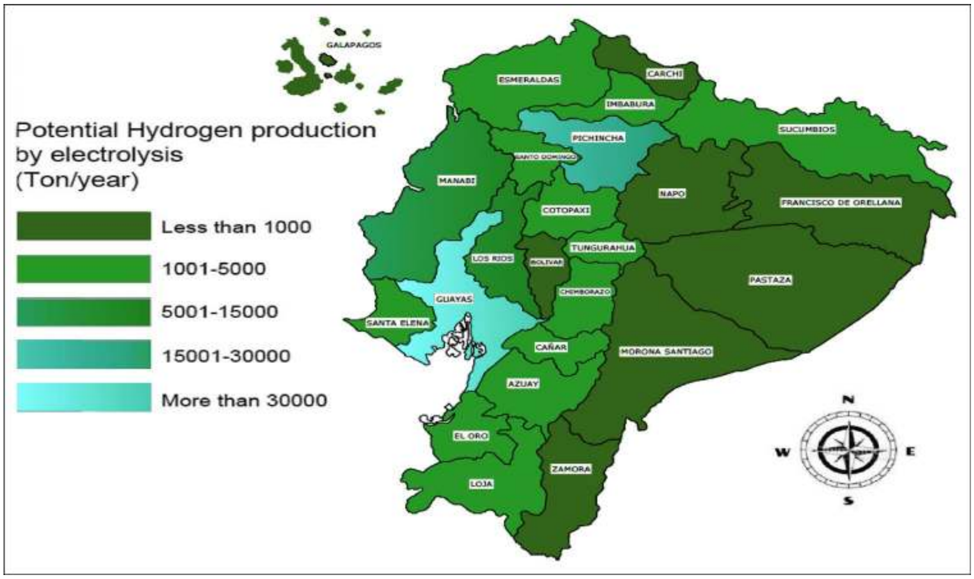

Fig. 8 Hydrogen production potential by GWE (2016)

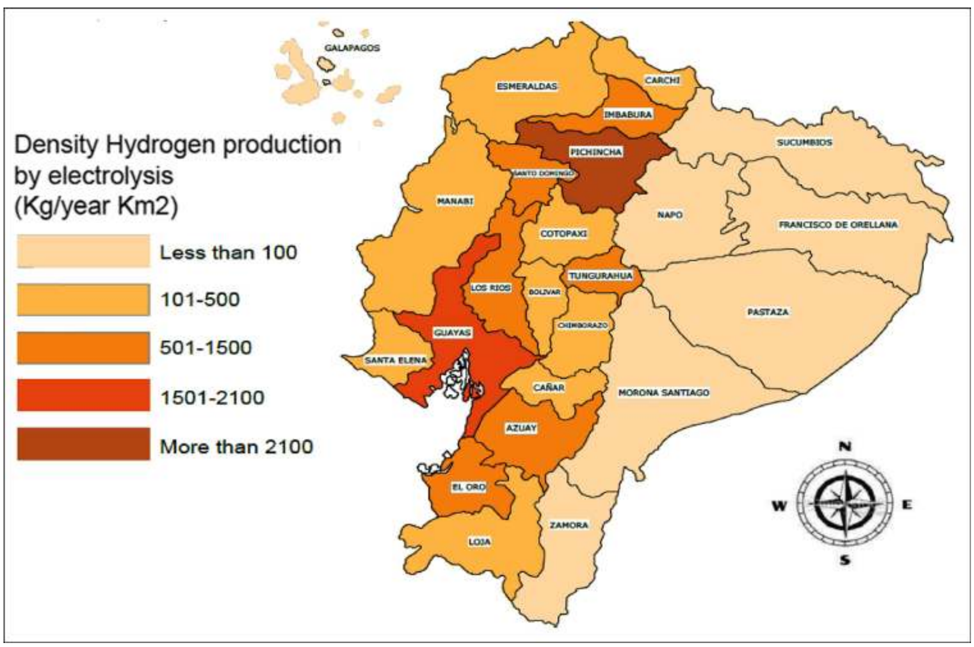

Fig. 9 Hydrogen production density potential by GWE (2016)

associated GHG reductions—is currently considered to be one of the country's primary national energy policy goals.

The diesel fuel substitution proposed for urban transportation in each of the provinces was calculated using the GWSR results, and the following complementary information: (a) the diesel fuel supply of each province, plus a minimum percentage destined for transportation (61%); (b) diesel fuel consumption in urban transportation (5%); (c) energy equivalence between the corresponding energy vectors (1 kg $H_2 = 3.3$ L of diesel fuel) [23]. The results of this analysis are presented in Fig. 10. It can be seen that the potential H_2 output could fulfil the urban transportation diesel fuel demand in 20 of the 23 provinces. In fact, potential H_2 production in the three largest jurisdictions, Azuay, Pichincha and Guayas (which together generate 57% of the country's MSW) was found to average 2.65 times their diesel demand for urban transportation. As an opportunity for future research, it is important to evaluate additional parallel uses for H_2 generated in order to complement the current proposal with other relevant H_2 demands.

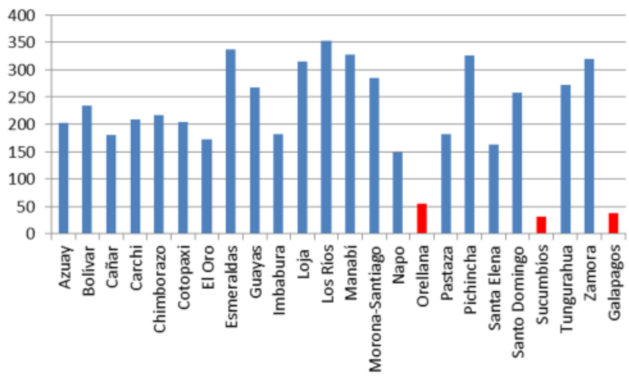

Fig. 10 Percentage diesel substitution by H_2 per province

Conclusions

Hydrogen fuel production from the MSW generated in Ecuador is feasible using both GWSR and GWE methods, with the former demonstrating the largest potential yield. The geographical resource distribution indicates that the three most highly-populated provinces represent those with the greatest H_2 potential. The possible use of H_2 as an energy vector in urban transportation throughout the country could fulfil these energy demands in 20 out of 23 provinces; achieving an average replacement rate of 265% in the three provinces that generate a combined 57% of the country's total MSW; Guayas, Pichincha, and Azuay. It can thus be concluded that exploiting the biodegradable fraction of MSW as a feedstock in a non-conventional H_2 production process represents a promising energy strategy. This proposal offers several very promising potential benefits, among them a solution to the problem of urban MSW final disposal, along with improvements to the urban transportation infrastructure and the environmental indicators associated with it. The results of this paper can be employed as a baseline for further studies of greater detail into the three most advantageous provinces identified, which contain the country's three largest cities, in terms of further analysing the sustainability of the system.

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