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Preliminary estimation of electrolytic hydrogen production potential from renewable energies in Ecuador

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ABSTRACT

An initial assessment of the production potential of H_2 by electrolysis is performed in Ecuador with electricity from renewable sources. The renewable energies considered are: solar photovoltaic, wind, geothermal and hydropower. The information about their potential is based on maps of solar and wind resources, geothermal surveys, as well as estimates on mini-hydro and spilled turbinable energy from hydroelectric plants with reservoir. The amount of H_2 is obtained by considering a PEM electrolizer, with an efficiency of 75%, reaching a production of 4.55×10^8 kg/year in a likely scenario. Two different uses of H_2 are presented: 1) automotive transportation, replacing gasoline and diesel and, 2) rural energy, replacing firewood for cooking in rural households in the country. As a result, H_2 is able to replace 65% and 44% of the volumes of imported gasoline and diesel, respectively and the overall replacement of gasoline in 9 out of 23 provinces. Also, it is possible the total replacement of firewood in rural households in 20 provinces, and, under certain conditions, the H_2 surplus could be used to completely cover the electricity needs in the same rural households in 20 provinces. It is concluded that, there are certain opportunities in Ecuador to include H_2 in its energy matrix, contributing to improve the supply of secondary energy, raising the life quality in rural areas, mitigation of environmental pollution and strengthening the national economy. All this makes necessary to conduct more detailed technical and economic studies.

Introduction

The use of hydrogen, H_2, as a way of energy storage and transportation is considered frequently as a good alternative to fossil fuels, whose massive utilization creates dangerous environmental consequences. Moreover, the eventual collapse of oil and gas reserves in the medium term makes the current energy system unsustainable [1]. The interest in H_2 as an energy carrier is based on its unique properties, the

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Nomenclature

Acronyms

CELEC EP	Electric Corporation from Ecuador, Public Sector
CDM	Clean Development Mechanism
CIE	Corporación para la Investigación Energética
RE	Renewable energies
FC	Fuel cells
GDP	Gross Domestic Product
GHG	Green house gasses
GIS	Geographic Information Systems.
HHV	Higher Heat Value
LHV	Lower Heat value
MMBOE	Million barrels of oil equivalent
NREL	National Laboratory of Renewables Energies
PEM	Proton Exchange Membrane
PV	Photovoltaic
SHES	System Hydrogen Energy Systems
STE	Spilled Turbinable Energy
MEER	Ministry of Electricity and Renewable Energy

Parameters

A_P	Province area, km^2
F_{AP}	Available area factor by province, adimensional
F_{AE}	Availability factor (electrolysis), adimensional
F_{AG}	Availability factor (geothermal), adimensional
F_C	Capacity factor, adimensional
F_p	Plant factor, adimensional
g	Gravity acceleration, m/s^2
H_2 HHV	H_2 Higher Heat Value, kWh/kg
η_e	PEM electrolyzer efficiency, adimensionañ
η_{fv}	PV conversion efficiency, adimensional
ρ_{H20}	Water density, kg/m

Variables

I_{PA}	Mean annual global insolation by province, kWh/m^2 day
E_{PV}	Annual PV energy by province, GWh/year
P_G	Geothermal potential, MWe
E_{EG}	Geothermal electric energy, MWh
E_{MHYDRO}	Minihydro electric energy, MWh
P_{MHYDRO}	H_2 minihydro annual production, kg/year
H	Water head, m
V	Spilled volume, m^3
P_{H2H}	H_2 hydro annual production, kg/year
E_{EXC}	Excess energy, J
P_{H2R}	H_2 Net annual production, kg/year

possibilities to obtain it from different sources and processes, and the capacity to satisfy the basic energy requirements in every society sector for different applications such as mobile, static or portable [2,3].

However, to constitute H_2 as the basis of a sustainable and distributed energy system, it is mandatory its production from primary renewable sources, creating the Solar Hydrogen Energy System, SHES, where the primary source is any type of renewable energy, RE, and the secondary source is H_2. Also, the use of H_2 constitutes an important mechanism to overcome the difficulties of RE approaching, related to its intermittence and its low storage capacity in a larger scale [4]. Thus, the SHES is having an important technological and scientific development in all the stages of the structure and performance [5]. Subsequently, it is proposed the slow incorporation of H_2 in energy systems in several countries to expand the energy supply and to reduce the dependence on fossil fuels [6].

In this context, a previous key stage to SHES implantation in a region or country is the estimation of the H_2 amount that potentially could be obtained through RE that assure its production continuously. The results of such estimation could guide and define the realization of specific studies about the technical and economic feasibility of SHES implementation. This requirement has motivated researches in several countries to evaluate the potential production of H_2 from RE, which is considered in the next section.

Theoretical background

USA

The USA is one of the countries with the largest number of studies on the amount of H_2 that could be obtained from fossil primary sources -natural gas and coal- and renewables energies -wind, solar, biomass and nuclear hydropower-, all led by NREL [7–11]. In the case of RE, they estimated annual production of 1 billion ton H_2 when solar PV, wind onshore and biomass are the primary sources with water electrolysis and biomass gasification as production process. The results are expressed in maps of H_2 potential production normalized by the area of the counties of the country and obtained by techniques of geographic information systems, GIS.

When the studies per renewable source are specified, for the case of wind power, it has been quantified the wind potential for the production of H_2 in two studies by NREL. In the first study, it is presented a map output in every county in the country, for a total production of H_2 of 2.74×10^{11} ton [8]. In the second one, more accurate wind resource estimates are achieved, resulting in a H_2 production of 1.1×10^{12} ton/year for the whole country [10]. For its part, the use of the PV power in the H_2 production by electrolysis has been evaluated in the US based on records from insolation in geographical cells 40 km side, with a conversion efficiency of 10%. Under certain environmental restrictions and land use, an amount of 7.2×10^8 ton/year of H_2 is obtained [8]. This value increases after more accurate estimates of the PV usable potential, reaching the amount of 8.7×10^9 ton/year for the same previous conditions [10]. Finally, NREL has estimated the production potential of H_2 from Spilled Turbinable Energy, STE, assuming that 30% of the annual production of 1321 plants in the country of this kind, reaching a H_2 production of 1×10^6 ton for 2006 [9].

Argentina

In this country, it has been determined the production potential of H_2 with solar PV, wind and biomass as primary sources, using electrolysis and gasification as production processes. The results are presented in H_2 production maps related to the area of the provinces and departments, obtained through GIS tools, with a total production of around 1 billion ton H_2/year. If the H_2 produced were to be used in transport sector, it would cover broadly the energy requirements of all provinces, being the province of Chubut in the south, the one with the highest density of H_2 production, 464 ton/km^2 year [12]. Also in the province of Cordoba it has been evaluated the H_2 production potential from wind for using it in the transportation industry. This sector requires about 5.25×10^5 ton of H_2 to cover its annual energy consumption, while H_2 production is estimated at 3.74×10^7 ton/year, calculated for an efficiency of the electrolysis process of 75% [13]. In a recent study for the same province, the estimation of the wind resource is improved, valuing economically the production and transport of H_2 generated at a specific wind farm with a production cost of 9.41 USD/kg H_2 [14].

Regarding solar PV energy, the estimates were based on information from the Solar Atlas of the country. The values are expressed in terms of density of H_2 production by department, Mendoza being the department that excels with a higher value to 180 ton/year km^2 [12].

Brazil

The renewable H_2 production by electrolysis has been studied in a region located in the Northeast, with the electricity coming from hydropower in excess in combination with solar and wind power, achieving an H_2 volume of 56.26×10^6 m^3 H_2/year, allocating it mainly for export [15]. It has also been made an inventory of the STE in the 100 largest hydroelectric plants in Brazil, reaching 106 TWh, equivalent to 30% of total production in Brazil for 2008 and which would produce 3.22×10^6 ton of H_2 [16]. Also, it has been evaluated the STE that could be generated at the Iguazu dam, obtaining a maximum generation value of 1,054,899 MWh, while the electrical energy needed to produce the H_2 required to move the entire fleet of public transport in the city Foz do Iguacu, ranged between 1.5% and 8.5% of the STE [17]. Finally, in Ref. [18] the H_2 penetration in the country's energy matrix is studied, emphasizing on the ER as the origin of the processes for obtaining this vector, especially in hydropower and bioenergy. The installed capacity of the country's FC technologies is also analyzed in order to project their use in the transport sector.

Venezuela

In this country, 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 [19]. In the wind power case, the usable wind potential on the mainland is evaluated obtaining a value of 1.83×1010 kWh/year, which leads to a production of electrolytic H_2 of 3.3×10^5 ton/year. The production potential of H_2 from PV is close to 2.0×10^7 ton/year, calculated from satellite data records and limited to the Venezuelan mainland. In the case of hydropower, from its mini–hydro potential, defined as the potential of less than or equal to 50 MW per generation facility (reaching 4.5 GW), it is possible to obtain 7.1×10^5 ton H_2/year [19].

Ecuador

Ecuador is the area where this study focuses. In this country, it has been analyzed the production of H_2 from the STE Paute-Molino hydroelectric plant, located in the south of the country, quantifying a maximum output of 10,802 ton/year for energy use as input from various industrial processes [20]. This study complements one recently held in which the potential of H_2 production is estimated from historical values of STE actually available from the operation of this plant. Such a study proposes to use H_2 in urban public transport in the city of Cuenca and estimates the environmental and economic impact of replacing diesel-powered buses by FC-H_2 buses [21]. Regarding the potential use of other RE sources for H_2 production, studies are not known. A documentary research should be mentioned, that explores the opportunities and barriers to the development of the H_2 energy in Ecuador. That study shows a favorable scenario in which bioenergy and hydropower are the best placed sources for the production of renewable H_2, where rural energy and transportation are the most suitable sectors for its use [22].

Other countries

In addition, other countries have studied the potential of H_2 production for a particular RE source, being STE-hydropower the most analyzed. For instance, in Paraguay it has been studied H_2 production using STE Iguazu Dam (shared facility with Brazil), for use as fuel, combined with hydrometane in vehicles to replace natural gas [23]. In Colombia, it has been studied the production of H_2 from the STE Amoyá hydroelectric plant, located in the middle of the country, to provide energy in the form of electricity and heat, in a hypothetical population of 16,000 inhabitants located in the near the site of production of H_2 [24]. Meanwhile, in Canada it has been proposed the H_2 production using the STE of Taison Hydroelectric plant, located in northeast, which averages 63% of idle capacity, obtaining a maximum H_2 production of 7 ton/day [25]. Nepal has estimated the H_2 to be obtained according to the percentage of the STE used, reaching a maximum of 140,000 ton by 2020 [26]. From the above it can be deduced that H_2 production by electrolysis from hydropower is a fully developed, efficient technology. It is preferably used in countries with a high hydroelectric potential and enough installed capacity to enable them to have cheap electricity and H_2 production costs that could be competitive with those obtained by the conventional method of steam reforming of natural gas. The predominant trend in the H_2 production from hydropower is the use of the STE, in variable proportions depending on the conditions of design and operating hydroelectric power plants with reservoirs.

In the case of wind power, in Sweden they use GIS tools and calculate 2.56×10^9 ton/year of H_2 produced by using their wind resource. With only 2% of this production they could replace 50% of gasoline consumption in the country, emphasizing the economic and environmental benefits that entail

[27]. Recently in Algeria, a technical-economic study was performed in order to determine the wind generation technology with the lowest cost of H_2 production based on the estimation of the resource potential in several regions of the country. They get that the D7 Wind turbine offers the best performance in terms of capacity factor that leads to a production cost of USD 1.214/kg de H_2 [28]. Finally, in Hong Kong renewable resources such as solar PV, wind and biomass from the treatment of municipal solid waste are estimated for the production of electrolytic H_2. The total amount of H_2 would cover about 40% of energy consumption in the transport sector of Hong Kong [29].

In the case of geothermal energy, H_2 production may occur in different ways [30]: 1. Direct extraction of geothermal steam and subsequent separation of H_2, although it has proved its technical feasibility, viability must still be improved [31]; 2. Conventional electrolysis, with the required electricity from geothermal power plants; 3. High temperature electrolysis, using geothermal heat to reduce power requirements, also of geothermal source; 4. Thermochemical cycles, driven by geothermal heat. All these ways to obtain geothermal H_2 have been studied although the production by conventional electrolysis has greater perspectives. Electrolysis allows to obtain H_2 at relatively low cost when available cheap geothermal power, such as in Iceland, with generating cost of USD cents 3.7/kWh [32]. However, the valuation of H_2 that would result from the use of geothermal energy to a particular country or region is a topic slightly reported in the specialized literature. It is worth mentioning a recent technical-economic study on the production potential of H_2 and electricity in Algeria with CO_2 as the working fluid. By using GIS techniques it was found that the northeast region offers the greatest potential for producing both vectors and for getting the levelized cost of electrolytic hydrogen more competitive [33].

The analysis of these studies show that H_2 production by electrolysis, with electricity from renewable sources, and by bioenergy waste gasification are the processes used to estimate the H_2 potential, while the preferred use is transportation. It is also possible to infer a common procedure for calculation of potential renewable H_2 presented in successive stages: First, to have basic information available from renewable resource: wind speed and direction, direct and diffuse sunlight, volume of agricultural, forestry and livestock waste, solid waste or other indicators of this resource. This information is obtained from satellite measurements, land-based weather stations, statistics and information from field crops and agricultural residues of different kinds. Second, to estimate the theoretical renewable energy potential, by various statistical methods and GIS tools, and their representation on maps or potential charts. Third, to determine the resource effectively available and usable after considering technical, geographical and environmental constraints; capacity factors of technology and energy conversion efficiencies. Finally, to calculate the amount of H_2 obtainable by various processes, also considering the energy conversion efficiency and availability of the plant. This procedure will be useful for this study whose purpose is to make a preliminary assessment of the potential of H_2 production by electrolysis from renewable resources in Ecuador, where basic information becomes available. This quantification would be the starting point for more detailed studies in cases where a potential production of H_2 geographically located is conjugated with a possible end use. This sets a niche opportunity for H_2 penetration in the energy matrix of the country, contributing to its diversification, based on the preeminence of RE, aligned with Ecuador energy policy. The RE evaluated in this study are wind energy, solar PV, geothermal and hydropower. The ability to use bioenergy as a source for H_2 production in Ecuador will be analyzed in a companion article, due to the diversity of forms and processes to obtaining H_2 from it.

Methodology

The estimated amount of electrolytic H_2 to be produced takes place in two successive steps: in the first one, the electrical power available to the electrolysis process is calculated from the use of the RE included in this study. In the second step, it is calculated the amount of H_2 to be obtained by this mode of production. Subsequently, the potential end uses of H_2 are analyzed, considering the replacement of two energy carriers, fuel and firewood. The scope of this replacement is estimated taking into account, on the one hand, energy equivalence between them based on the LHV, and on the other, the demand for gasoline and fuel at the provincial level. Finally, to assess a complementary end use, the generation of electricity in rural households, the use of H_2-PEMFC is proposed. It should also be noted that the study is limited to the mainland of Ecuador, as the island territory, Galapagos Province, has its own resources and context. A description of the procedure in each case is presented below.

Estimation of power and electric energy according to each RE

Wind energy

The use of wind energy is based on the conversion of kinetic wind energy into electrical energy through wind turbines, whose technologies have improved their performance and efficiency that have led to a decrease in production costs. This explains, in large part, the wind energy industry growth during the last decade, moving from a global installed capacity of 48 GW in 2004 to 318 GW in 2014, equivalent to an average annual increase of 20% [34].

In Ecuador, to estimate the amount of H_2 that would result from the use of its wind potential, it is possible to start with the information contained in the Ecuador's Wind Atlas with power generation purposes. The Atlas is developed on the MesoMap system, coupled with simplified wind flow microscale model, WindMap, generating a set of maps of annual wind speeds for the mainland with a resolution of 200 m. One of these maps is presented in Fig. 1 [35].

For the calculation of the electric potential in the Wind Atlas, the provinces of the country with average wind speeds over 6 m/s were selected. This speed is available in 12 out of 23 provinces, mostly located in the Sierra region. The technical electrical potential that could be obtained at wind farms located in the chosen provinces is calculated for the following conditions:

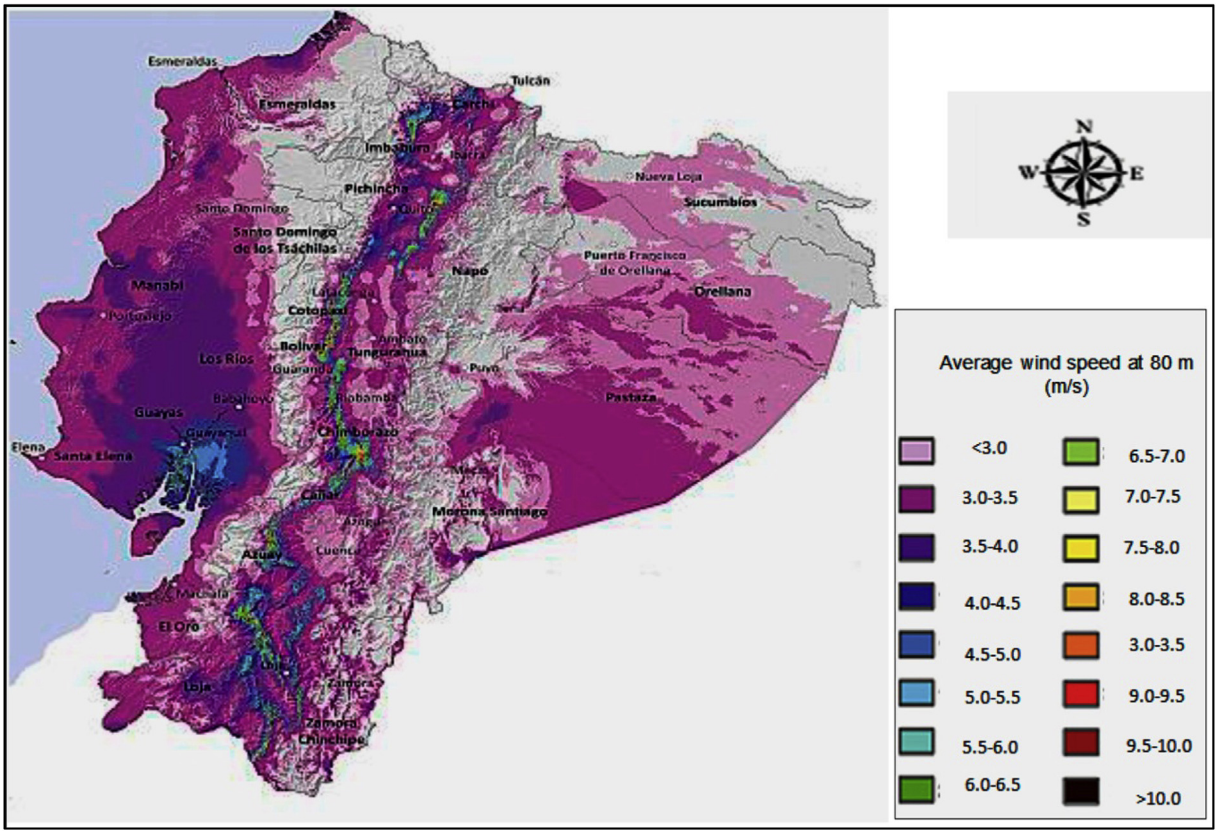

Fig. 1 – Average wind speed at 80 m. Year 2013 [35].

- Areas with annual average speeds equal to or greater than 6 m/s
- Average performance curves of commercial wind turbines installed at 80 m height, calculated for the lower limits of each interval of 0.5 m/s
- Average density of occupation of land of 3 MW/km^2
- Availability factor of 0.98, typical for commercial wind farms
- Capacity factor between 0.2 and 0.35, calculated on the basis of the annual average wind speed.
- Exclusion of natural areas covered by water and protected areas
- Air density at 3500 m, equal to 0.87 kg/m^3

The average power expected for the existing winds regime in the selected provinces, and the associated electric energy, are presented in maps of potential, as shown in Fig. 2. Details of the wind generation model and the calculation method of power and energy are in Ref. [35].

Solar energy

In this case, PV solar energy is considered. This technology has a pronounced growth in the last decade and a worldwide installed capacity of 177 GW by 2013 [34]. For Ecuador, similar to the wind case, the base information for estimating H_2 from Solar PV is the Ecuador Solar Atlas, made from NREL records of direct, diffuse and global daily insolation on horizontal surface cells of approximately 40 km × 40 km. Through a process of filtering basic information, it is obtained 472 valuation points of the solar resource for the Ecuadorian mainland. Subsequently, by statistical interpolation, insolation values are generated in cells with a resolution of 1 km^2 [36]. Results are expressed in average monthly and annual maps, as shown in Fig. 3.

The electricity could be obtained by converting the overall average annual insolation and it depends on a set of parameters. The first one is the percentage of the area available in each province, F_{AP}. Restrictions for installation and operation of PV modules, are similar to the wind power case and deal with protected geographic areas, water bodies and especially the urban centers and scattered populations, therefore the population density is important to set a value of F_{AP} indicator. Thus, in USA the indicator takes a value of 3% [10]; while in Argentina it has been chosen 4.5% [12]. This study has assumed a value of 2%, as the population density of Ecuador is about double the US and three times that of Argentina [37]. For efficiency PV conversion, η_{fv}, it is assumed a value of 17%, an average value of the commercial supply of PV modules consulted [19,38]. Thus, the expression for calculating the usable energy from solar PV energy by province is:

$$E_{FV}\ (\text{kWh/year}) = I_{PA} \times \eta_{fv} \times A_P \times F_{AP} \times 365 \times 10 \tag{1}$$

where I_{PA} is the average total annual insolation by province, obtained by filtering process of global insolation data of the entire Ecuadorian mainland, while the numerical value '10′ is a conversion factor between units of different variables. To

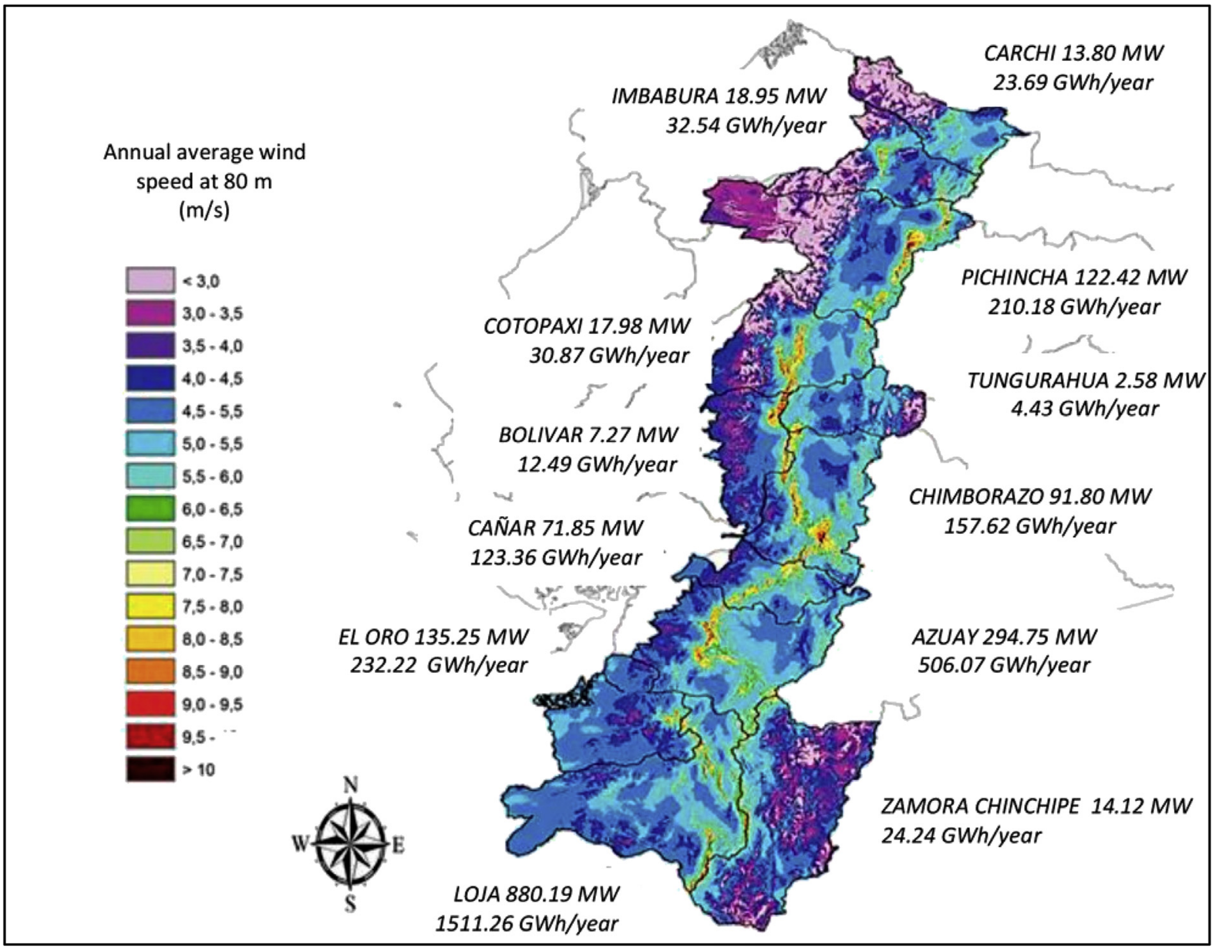

Fig. 2 – Technical wind potential (MW) and wind power (GWh/year) in selected provinces [35].

illustrate the calculation process, the case of Loja province is presented, which is the one with the highest global annual average insolation, then:

$$E_{FV} = (5{,}109\ \text{Wh/m}^2)\ (0.17)\ (11{,}065\ \text{km}^2)\ (0.02)\ (365\ \text{days})\ (10) = 7.02 \times 108\ \text{kWh/year} \quad (2)$$

This calculation is repeated for all the provinces of mainland Ecuador and its results are expressed on a map of electrical power, Fig. 7.

Geothermal energy

The technologies associated with the use of geothermal energy, using heat from the earth to produce electricity, are direct thermal applications and heat pump [39]. Geothermal energy has several competitive advantages over other ER: wide availability in uptake and high efficiency in conversion to electricity, resulting in lower generation costs [40]. Today, many countries use geothermal energy for electricity supply. Table 1 shows the ten countries with the largest installed geothermal capacity.

The geothermal potential can be understood as the amount of thermal energy between the surface of the earth and a specific depth, measured with reference to the local annual average temperature [41]. It is estimated that this geothermal resource is of great proportions accounting the global technical potential of 5000 EJ/year, far superior to other RE [30]. Its theoretical and practical potential is usually expressed in terms of the electrical power to be generated, P_G. The expression used to calculate the corresponding annual electricity is [34]:

$$E_{EG} = P_G \times F_C \times F_{AG} \times 8760 \quad (3)$$

where the parameter capacity factor, F_C, is taken equal to 85%, the average value reported in the literature [39,40,42], while for the availability factor, F_{AG}, it has taken a value equal to 95% [40]. By applying this equation it is obtained the geothermal electricity from the geothermal prospects in prefeasibility stage in Ecuador. For example, for the Chacana geothermal prospect, the result is (eq. (4)):

$$E_{EG} = (418\ \text{MW})\ (0.85)\ (0.95)\ (8760\ \text{h}) = 2.96 \times 106\ \text{MWh} \quad (4)$$

Hydropower

The estimation of the amount of H_2 obtainable from the hydroelectric potential for a country or region can be done by two methods, without ruling out other methodological approaches.

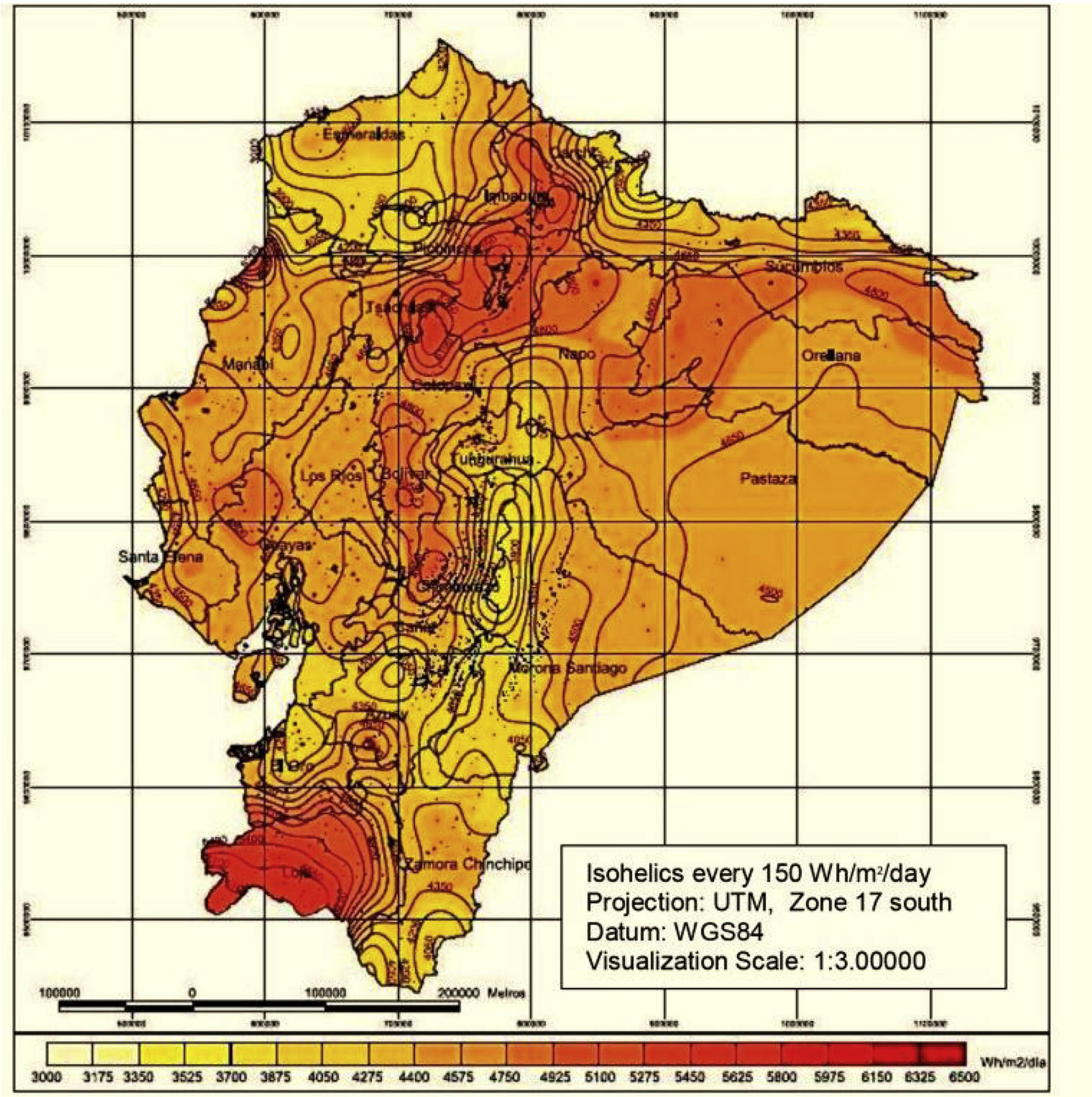

Fig. 3 – Average total annual insolation in Ecuador (Wh/m^2/day) [36].

Table 1 – Countries with the largest capacity of geothermal power generation.

Country	Capacity (GW)
United States	3.5
Philippines	1.9
Indonesia	1.4
Mexico	1.0
New Zealand	1.0
Italy	0.9
Iceland	0.7
Kenya	0.6
Japan	0.5
Turkey	0.4

Source [34].

The first method is simply to assume that a percentage of the available hydro potential is intended for the production of H_2. In this regard, this study considers to harness the potential of mini-hydro type, such as proposed in Ref. [19]. The procedure is to estimate the percentage of the total hydropower potential corresponding to mini-hydro potential and then to calculate the electric energy associated, depending on the availability of generation and the capacity factor. The second way to assess the available hydropower potential for the production of H_2 is based on using the Spilled Turbinable Energy, STE, understood as the power that could be generated from turbinable water that should be discarded for various reasons.

H_2 production by electrolysis

Once the potential of generating electricity is known, this is used to produce H_2 into a PEM electrolyzer with efficiency, η_e,

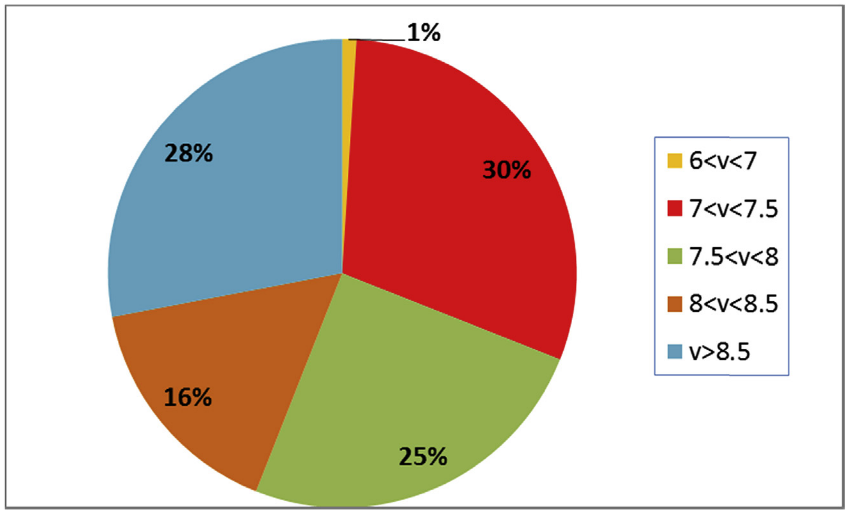

Fig. 4 – Distribution of wind speed regimes in selected provinces of Ecuador.

of 75% based on HHV of H_2, and an availability of the electrolytic plant, F_{AE}, of 95%, values used in several studies on this mode of H_2 production [16,19,43]. Then:

$$P_{H2} = (E_D \times \eta_e \times F_{AE})/HHV \quad (5)$$

where E_D is the power available for the production of H_2 and may correspond to a value: for the whole country, in the case of hydroelectric mini-hydro; for a province, in the case of solar PV and wind power; or for a specific geographical location, in the case of geothermal energy and hydropower type STE. For example, for the E_{FV} calculated in (2) for the province of Loja, with $E_D = E_{FV}$ it results (eq. (6)):

$$P_{H2} = (7.02 \times 10^8 \text{ kWh/year} \times 0.75 \times 0.95)/(39.4 \text{ kWh/kg } H_2) = 1.27 \times 10^7 \text{ kg } H_2\text{/year} \quad (6)$$

Also for the geothermal electricity from the Chacana prospect, equation (4), with $E_D = E_{EG}$:

$$P_{H2} = (2.96 \times 10^9 \text{ kWh/year} \times 0.75 \times 0.95)/ (39.4 \text{ kWh/kg } H_2) = 5.35 \times 10^7 \text{ kg } H_2\text{/year} \quad (7)$$

Final uses

The H_2 performance for the proposed end uses is weighted based on the energy equivalences among the vectors involved, referring to the LHV of each vector [21,44], and on gasoline and firewood consumption by province [45,46] while the production of H_2 in each province is equal to the sum of the output obtained for the different RE sources considered. Thus:

$$1 \text{ kg } H_2 \text{ (liquid)} = 2.78 \text{ kg gasoline} = 7 \text{ kg firewood} \quad (8)$$

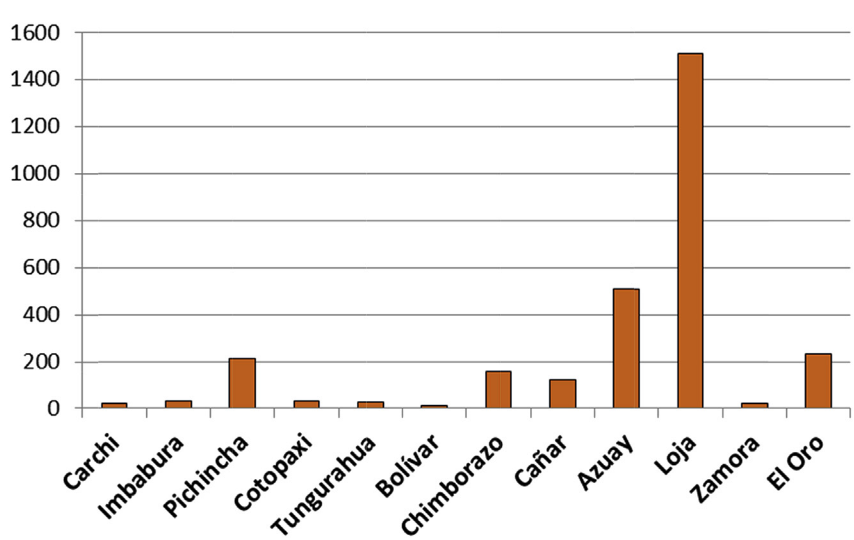

Fig. 5 – Electric energy potential from wind power in selected provinces (GWh/year).

Table 2 – H_2 production from wind energy by province and overall.

Province	P_{H2} (kg H_2/year)
Carchi	4.28×10^5
Imbabura	5.88×10^5
Pichincha	3.84×10^6
Cotopaxi	5.58×10^5
Tungurahua	4.97×10^5
Bolívar	2.26×10^5
Chimborazo	2.85×10^6
Cañar	2.23×10^6
Azuay	9.15×10^6
Loja	2.73×10^7
Zamora-Chinchipe	4.38×10^5
El Oro	4.20×10^6
Total	$\mathbf{5.23 \times 10^7}$

To illustrate the calculation method, it is considered the following hypothetical case:

Gasoline consumption in the transport sector in the province A: 100,000 kg/year.

Firewood consumption in rural households in the province A: 100,000 kg/year.

Renewable H_2 production in the province A: 30,000 kg/year.

Then:

H_2 consumption equivalent to fuel consumption: 35,971 kg/year.

H_2 consumption equivalent to the consumption of firewood: 14,286 kg/year.

Percentage of substitution: (Production H_2/H_2 consumption equivalent) x 100.

For gasoline: $(30000/35971) \times 100 = 83\%$

For firewood: $(30000/14286) \times 100 = 200\%$

Results

Wind energy

From the information of the Wind Atlas on the wind regimes in selected provinces, it has been calculated the distribution of

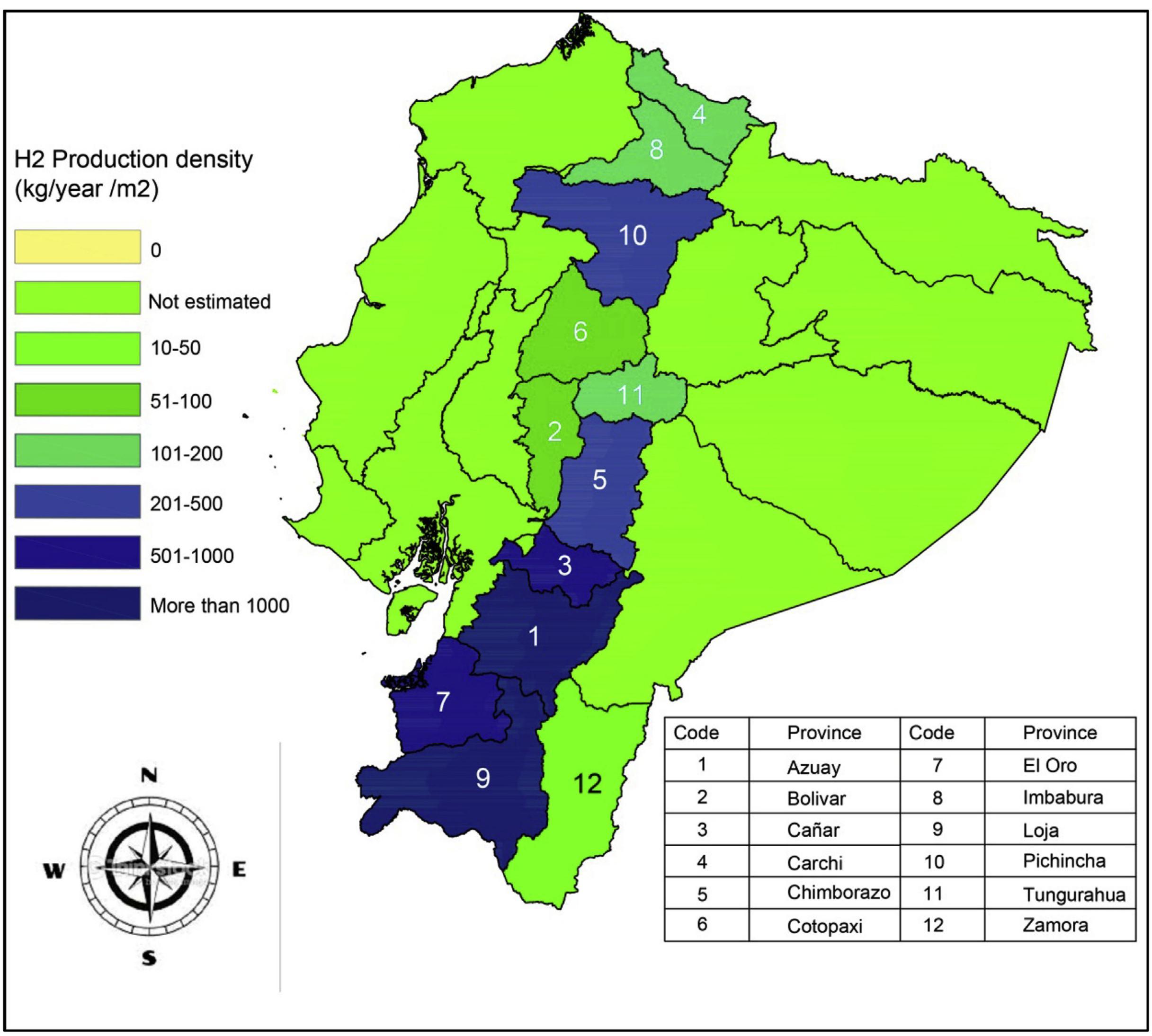

Fig. 6 – H_2 Production density from wind energy.

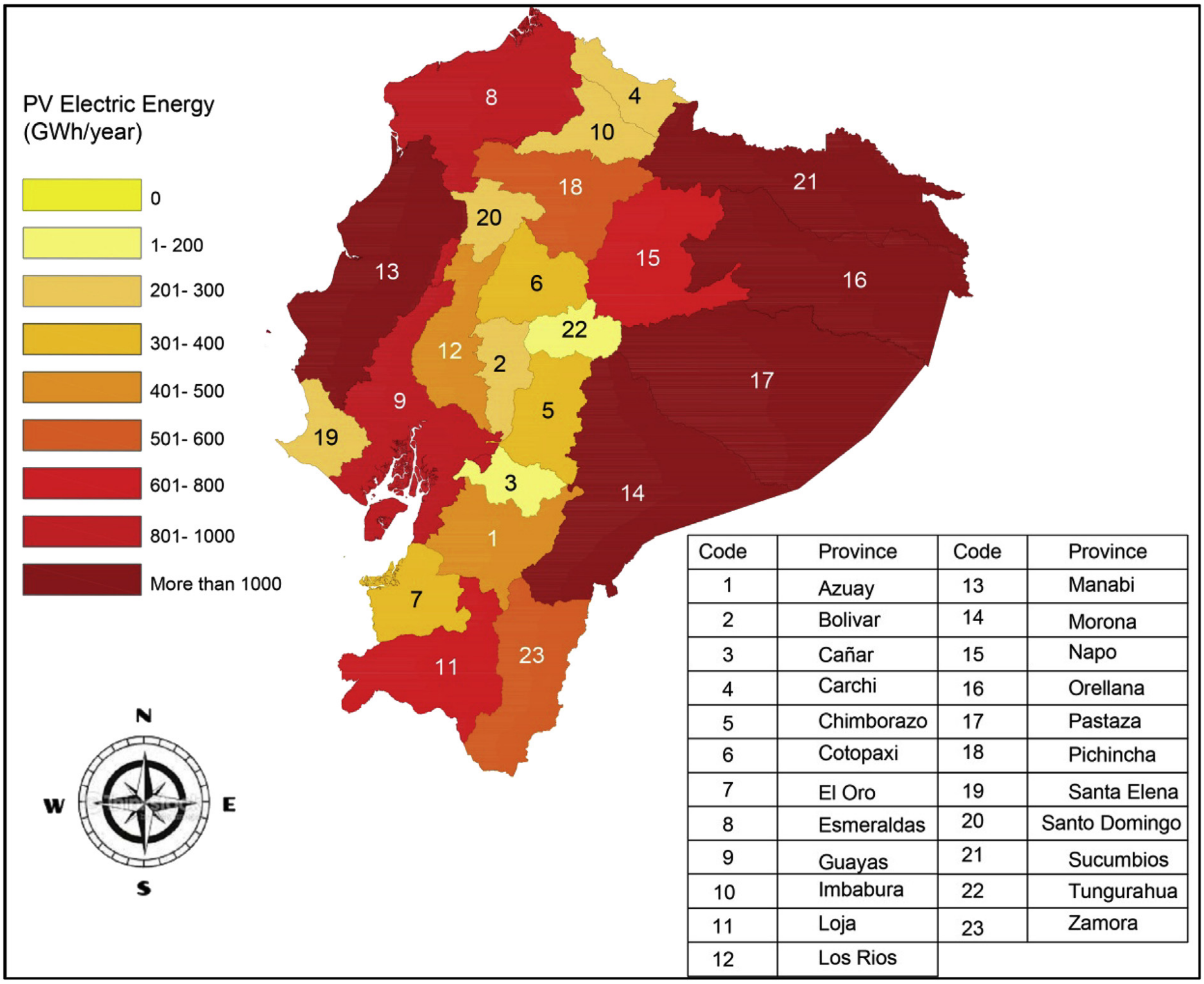

Fig. 7 – PV Electricity by province (GWh/year).

Table 3 – H_2 production from PV by province and total.

Province	P_{H2} (kg H_2/year)
Azuay	8.00×10^6
Bolívar	4.25×10^6
Cañar	3.14×10^6
Carchi	3.85×10^6
Chimborazo	6.46×10^6
Cotopaxi	6.58×10^6
El Oro	5.83×10^6
Esmeraldas	1.50×10^7
Guayas	1.58×10^7
Imbabura	4.95×10^6
Loja	1.27×10^7
Los Ríos	7.52×10^6
Manabí	1.82×10^7
Morona	2.36×10^7
Napo	1.33×10^7
Orellana	2.29×10^7
Pastaza	3.06×10^7
Pichincha	1.03×10^7
Santa Elena	3.80×10^6
Santo Domingo	4.06×10^6
Sucumbíos	1.85×10^7
Tungurahua	3.29×10^6
Zamora	1.02×10^7
Total	$\mathbf{2.55 \times 10^8}$

wind speed on intervals of 0.5 m/s, Fig. 4, noting that speeds above 7.5 m/s constitute 69% of the existing regime of winds.

In Fig. 5, the values of wind power between the provinces considered are compared. It stands Loja province in the south is highlighted as it has in operation, since year 2013, the Villonaco wind farm with 11 wind turbines that provide a total installed capacity of 16.5 MW with an average plant factor of 52.4% that supports a CDM project. In addition it has been projected a second wind farm in the same province with a design capacity of 50 MW [47].

The overall annual production by province is shown in Table 2. In Fig. 6 the respective output density is represented where is worth to note that adjacent Andean provinces located in the south, Azuay and Loja, have the highest densities of all provinces included in the study.

Solar FV energy

The map of the provincial distribution of FV electricity is shown in Fig. 7, appreciating that, as expected, the provinces from both regions (Coast and Oriente) have the largest values of PV power generation.

The results of PV H_2 production are presented in Table 3 and the calculation procedure is similar to the wind power

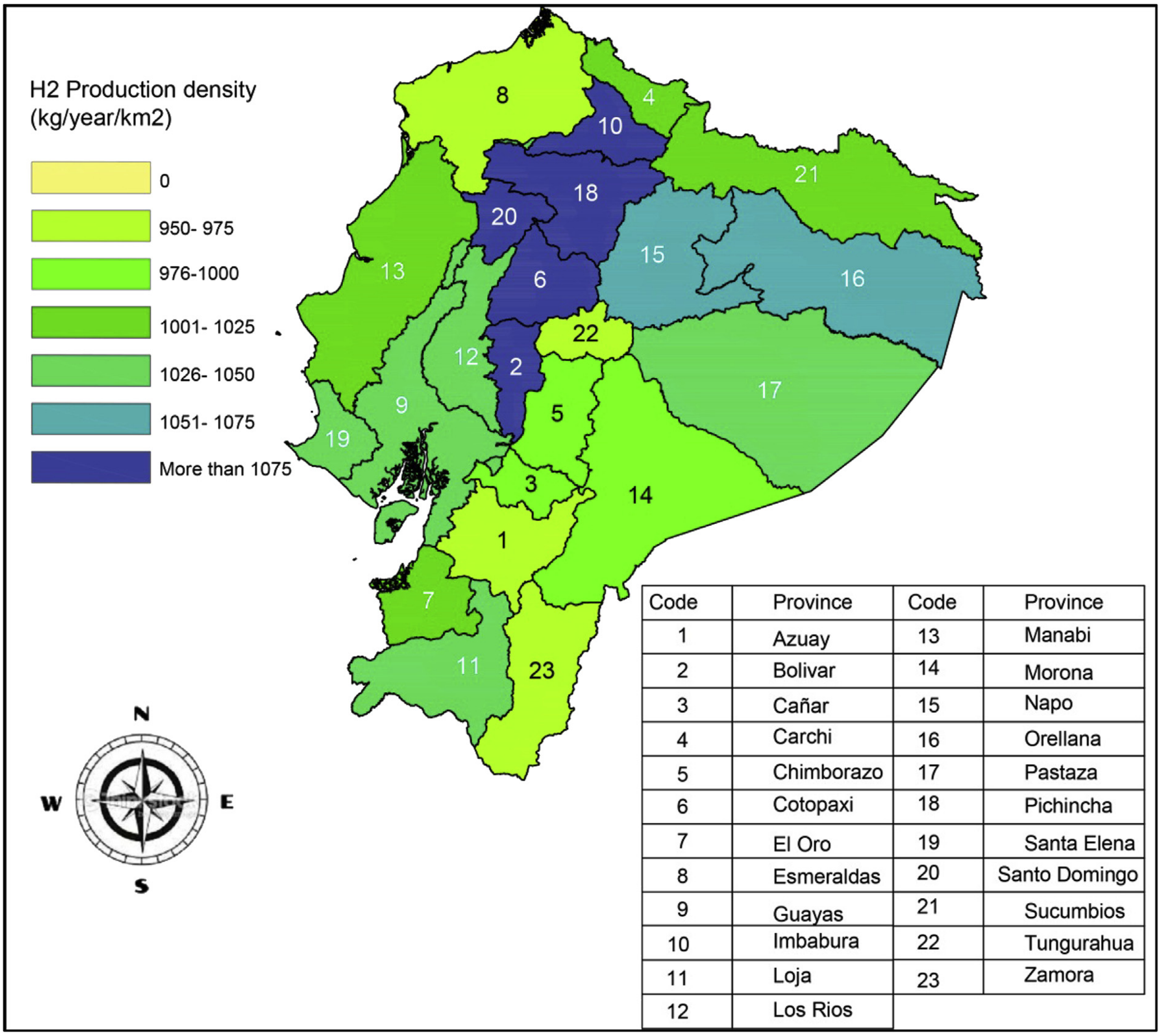

Fig. 8 – H_2 production density by province from PV energy (kg/year km^2).

case. The densities of H_2 production by province are shown in Fig. 8. The provinces located in the Sierra Central region: Bolivar, Cotopaxi, Santo Domingo, Pichincha and Imbabura, offer the greatest values although they are not the ones of the highest production.

Geothermal energy

In Ecuador, the estimates of its geothermal potential have changed over time [48–51]. The most updated study is presented in Refs. [51], where the theoretical potential is between 6500 MW and 8000 MW. These values were calculated using the empirical relationship proposed in Ref. [52] by adding the number of active volcanoes and geothermal potential, noting that the country has between 30 and 40 active volcanoes. This potential, higher than the total installed capacity of Ecuador in 2014, leads to determine the technical potential with a value of 952 MWe, obtained from feasibility studies for four geothermal prospects of high temperature, three of which are ready for deep exploration. There are also eleven prospects in recognition stage, four with high temperature and the remaining with fluids at most suitable temperatures for direct use. These prospects are shown in Fig. 9.

The amount of geothermal H_2 is obtained by using equation (5), with $E_D = E_{EG}$. The results, depending on the potential used are shown in Table 4.

Hydro energy

The theoretical hydropower potential of Ecuador is obtained of the total average flow calculated in 15,123 m^3/s, and the difference in levels, giving a value of approximately 93,400 MW, equivalent to 615,175 GWh/year [53]. Meanwhile, in Ref. [54] the country's hydroelectric potential is 91 GW for theoretical potential; 31 GW and 22 GW for technical and economic potentials, respectively. It must be subtracted from the latter, the installed and under construction plants, obtaining a value of 16,392 MW of untapped potential. Considering the first way of H_2 assessment from the hydroelectric potential, and after reviewing the hydroelectric generation projects in Ecuador registered at the Agency for Regulation and Control of Electricity (Agencia de Regulación

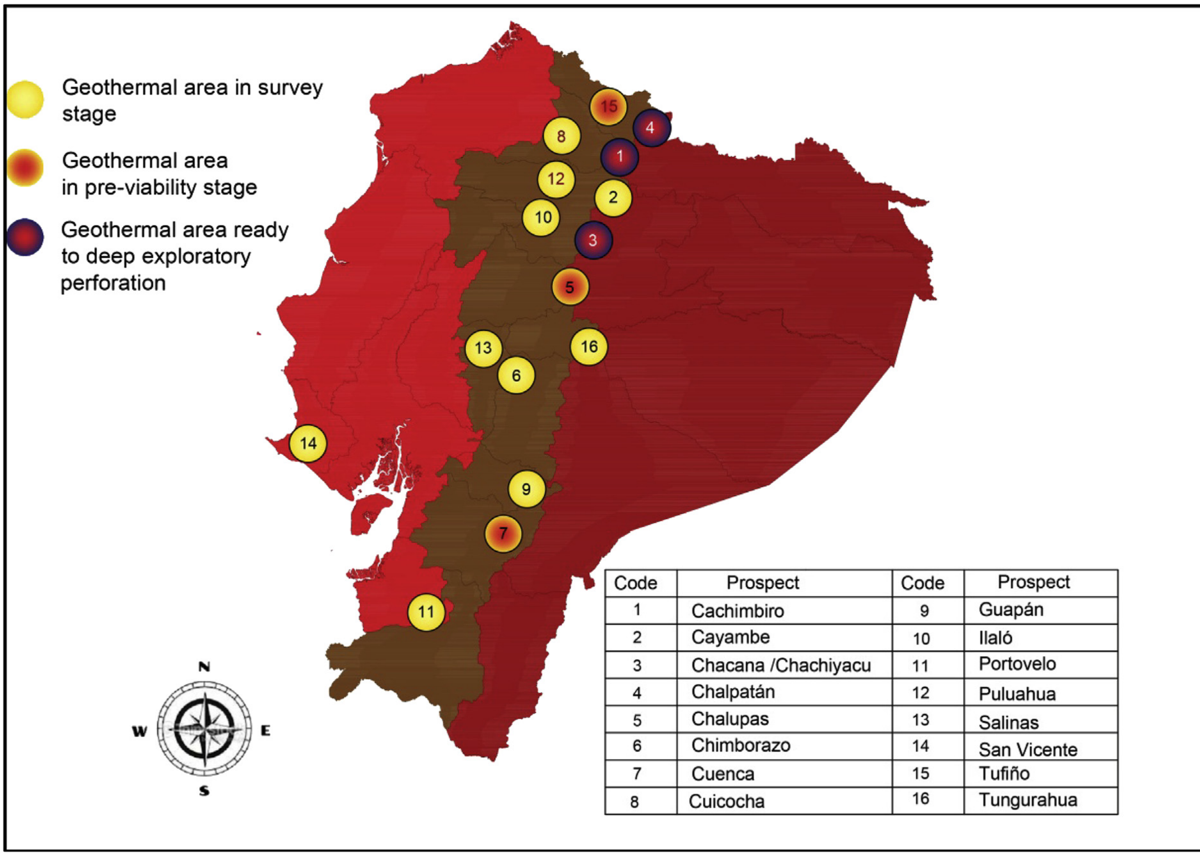

Fig. 9 – Geographical location of the main geothermal potential. Source: adapted from Ref. [51].

y Control de la Electricidad, ARCONEL), it is concluded that about 10% is mini-hydro type [55]. Therefore, it is valid to assume that 10% of the untapped hydropower potential that is economically available is mini-hydro, such that:

$$P_{MHYDRO} = (16{,}392\ \text{MW})\ (0.1) = 1639.2\ \text{MW} \quad (9)$$

The corresponding electricity is calculated assuming its availability throughout the year and a plant factor, F_p, 57%, the average value of the operation of Paute-Molino plant, the largest capacity central of the country during 2010–2014 [56], such that:

$$E_{MHYDRO} = (1639.2\ \text{MW})\ (8760\ \text{h})\ (0.57) = 8.18 \times 10^6\ \text{MWh} \quad (10)$$

From equation (5), it is obtained the amount of H_2 for $E_D = E_{MHYDRO}$

$$P_{H2} = 1.48 \times 10^8\ \text{kg/year} \quad (11)$$

This result corresponds to the ideal case in which the entire mini-hydro potential is used for the production of H_2. In a more adjusted to reality scenario, it is established an average utilization rate of 30% of this potential, taking into account limitations related to the hydrological cycle and technical standards [57]. So:

$$P_{H2R} = 4.4 \times 10^7\ \text{kg/year} \quad (12)$$

The second way to assess the amount of H_2 in Ecuador is to use the STE of the four largest hydroelectric power plants with

Table 4 – Production of H_2 from geothermal potential.

	Potential (MWe)	Electric energy (kWh/year)	H_2 production (kg/year)
Theoretical	6500–8000	4.60×10^7–5.66×10^7	8.31×10^8–1.02×10^9
Technical	(1) 138	9.76×10^5	1.77×10^7
(1) Tufiño	(2) 113	7.99×0^5	1.45×10^7
(2) Chachimbiro	(3) 283	2.00×10^6	3.62×10^7
(3) Chalupas	(4) 418	2.96×10^6	5.35×10^7
(4) Chacana			
Total Technical	**952**	**6.73×10^6**	**1.22×10^8**

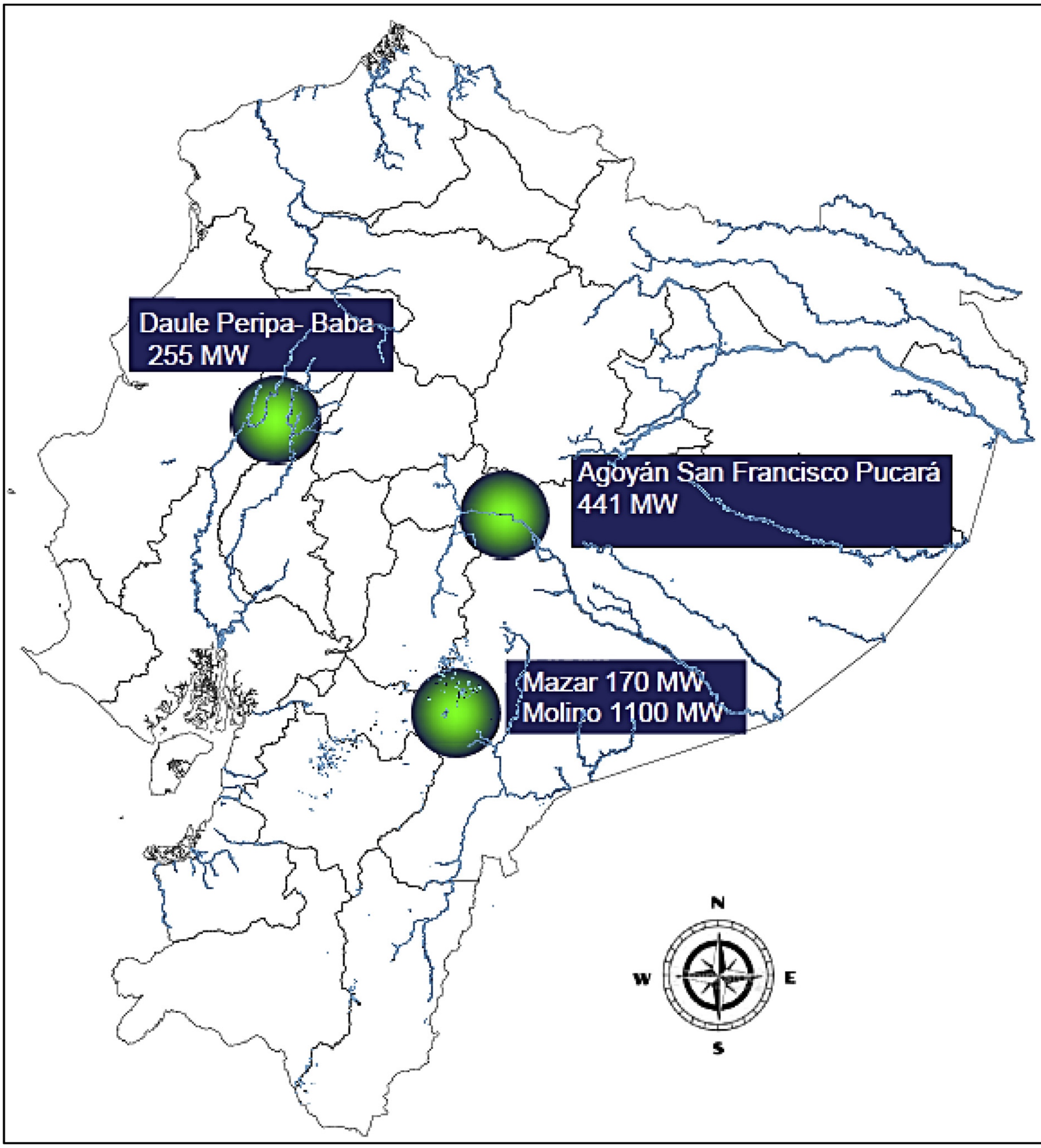

Fig. 10 – Location of hydroelectric plants with reservoirs in Ecuador. Source:adapted from Ref. [58].

reservoirs in operation: Paute-Molino, Amaluza reservoir; Paute Mazar, Mazar reservoir; Agoyán, Pisayambo reservoir; and Daule-Peripa, with its reservoir of the same name. In Fig. 10, it is presented the approximate geographical location, adapted from Ref. [58]:

The evolution of spills in each of the mentioned reservoirs, in the period 2007–2013, is presented in Table 5 [59], considering that the hydrological behavior of the reservoirs in a given period is a better indicator.

Table 5 – Spills by reservoir and annual totals. 2007–2013 period ($m^3 \times 10^6$).

	2007	2008	2009	2010	2011	2012	2013
Amaluza	770	704	379	14	778	273	179
Mazar	0	0	0	149	715	208	517
Pisayambo	0	0	0	0	1	171	74
Daule-Peripa	0	1807	0	0	199	1646	385
Total	**770**	**2511**	**379**	**163**	**1693**	**2297**	**1156**

Table 6 – Maximum and restitution heights in reservoirs (m).

	Amaluza	Mazar	Pisayambo	Daule-Peripa
Maximum height of operation (m)	1991	2153	3569	85
Restitution height (m)	1323	2007	3125	17

It is also important to know the maximum level of reservoir operation, which represents the height limit before the dumping occurs; and the restitution height, defined as the height at which the river water is replenished, Table 6, both measured quantities relative to sea level (masl). The difference between the two levels represents the net usable head to take into account in calculating the STE.

From this information the amount of available energy is obtained by Ref. [12]:

$$E_{EXC} = \rho_{H20}\, g\, V\, H \quad (13)$$

Finally, from equation (5), with $E_D = E_{EXC}$, the production of H_2 for two situations is obtained: first, it is assumed that all STE average available is intended for such production, while in the second scenario a percentage of that energy is used. The first case is the ideal and may be taken as a benchmark; while the second one corresponds to a more adjusted situation to reality, and its value is obtained from the actual operation of the first two plants (Amaluza and Mazar), and an estimation for the other two (Daule-Peripa and Agoyán) [59]. The results are shown in Table 7.

Then, the total potential of H_2 production from hydroelectric sources in Ecuador, taking into account both estimation pathways is 1.67×10^8 kg/year in the theoretical case and 4.61×10^7 kg/year in the feasible case.

Total production of electrolytic renewable H_2 in Ecuador

The total annual H_2 production obtained from the use of the potentials of the RE considered in this study are summarized in Table 8. The distribution average, for the technical potential, is shown in Fig. 11, in which solar PV is the largest contributor.

Comparing these results with those of other countries for the same type of RE, Table 9, it can be seen that the total production potential and density of renewable H_2 for Ecuador are the lowest. However, it must be clarified that in addition to being the smallest of the three countries compared, the results are heavily influenced by theoretical estimates of renewable resource and parameters used in potential calculation of RE as well as in the production of H_2. In any case, the amount of H_2 that could be produced in Ecuador could become an important mechanism to improve and diversify the country's energy matrix and contribute to sustainable development of both transportation and the rural sector, which is discussed in the next section that deals to the possible uses of renewable H_2.

End uses of H_2

The possible end uses of renewable electrolytic H_2 in Ecuador are focused on two sectors already identified as potential niche opportunity: automotive transportation and rural electrification [22]. In the first sector, it is proposed to use the H_2 in vehicles driven by FC replacing vehicles powered by gasoline and diesel fuel, both with large volumes from foreign origin in the country [46]. Taking into account the energy equivalence between these energy carriers, it is determined that the feasible (technical) H_2 production would be enough to cover 65% and 44% of the total imported volume of gasoline and diesel, respectively, in 2013. This substitution would have several positive effects: first, helping to reduce the deficit in the production of secondary energy and contribute to the diversification of the energy matrix; second, it would reduce GHG emissions in the transport sector, the main contributor of thereof; and third, improving public finances by reducing the amount of imports of the country [60]. When the availability of H_2 to replace gasoline consumption is valued in percentage terms, based on the H_2 production feasible in each province, the replacement ranges between a minimum of 6% and a maximum value of 1095%. In addition, in 9 provinces (39% of total) H_2 fully satisfied their gasoline consumption, Fig. 12. These results would merit a more detailed analysis in these

Table 7 – H_2 produced from the use of STE. Ideal and real scenario.

Central	STE Ideal scenario (kWh/year)	Production (kg/year)	Usable Porcentaje STE	STE Real scenario (kWh/year)	H_2 production (kg/year)
Paute- Molino	8.05×10^8	$1{,}46 \times 10^7$	11.9	9.6×10^7	1.73×10^6
Paute-Mazar	9.03×10^7	$1{,}63 \times 10^6$	8.2	7.4×10^6	1.34×10^5
Daule-Peripa	1.07×10^8	$1{,}93 \times 10^6$	8	8.6×10^6	1.55×10^5
Agoyán	4.26×10^7	$7{,}71 \times 10^5$	8	3.4×10^6	6.17×10^4
Total	$\mathbf{1.04 \times 10^9}$	$\mathbf{1{,}88 \times 10^7}$	**9**	$\mathbf{1.15 \times 10^8}$	$\mathbf{2.08 \times 10^6}$

Table 8 – Production of electrolytic H_2 from RE (kg/year).

	Wind tech.	Solar tech.	Geothermal		Hydro energy			
			Theor.	Tech.	Mini theor.	Mini factible	STE theor.	STE factible
H_2 production	5.23×10^7	2.55×10^8	8.31×10^8	1.22×10^8	1.48×10^8	4.4×10^7	1.88×10^7	2.08×10^6

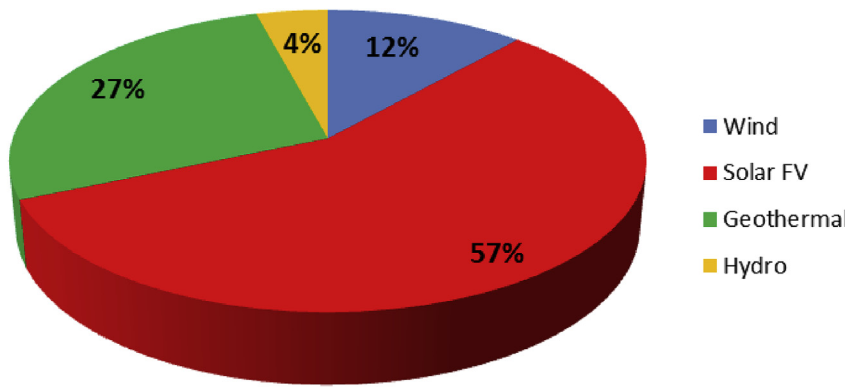

Fig. 11 – Distribution average annual H_2 production according to RE.

Table 9 – Production potential of renewable H_2 in Ecuador as compared to other countries (kg/year).

Country	Solar H_2	Wind H_2	Mini hydro H_2	Total production (kg/year)	Production density (kg/year/m^2)
Ecuador	2.55×10^8	5.23×10^7	1.48×10^8	4.55×10^8	1.62×10^3
EE. UU.	8.70×10^{12}	7.26×10^{11}	1.00×10^9	9.43×10^{12}	9.59×10^5
Venezuela	1.97×10^{10}	3.30×10^8	7.13×10^8	2.07×10^{10}	2.27×10^4

provinces that includes, in addition to determining the most convenient RE source, technical and economic studies of different stages of the implementation of SESH: production, storage, transportation and infrastructure supply to the end user.

In the second sector, it is intended to replace firewood by H_2 as a heat source for cooking, taking into account that this biomass is routinely used in 18% of rural households in the country, equivalent to 241,292 households [45]. Firewood is an inefficient and polluting source of energy for cooking. The distribution percentage of these households by province (Fig. 13) shows the existence of 5 provinces with a utilization rate of firewood of 35% or more.

To determine whether it is possible to replace the wood by the H_2 as a heat source, first firewood consumption in rural households in each province is calculated, taking into account national residential consumption of this fuel [60] as well as the percentage of rural households that use firewood in each province [45]. Then energy equivalence between wood and H_2, based on the LHV of both [44], is calculated in order to determine de amount of H_2 required in each province, with the result that it is possible to comprehensively cover the requirements of firewood in 20 of the 23 provinces of the country, Table 10.

In the 20 provinces with surplus it could be given a complementary use of H_2, the supply of electricity generated in H_2 FC to 142,200 rural households that do not have this basic service, and equivalent to 10% of total national rural households [45]. Fig. 14 shows the percentage of households without electricity, by province.

To assess this additional use of H_2, it is assumed that both the use of firewood for cooking and lack of electricity take

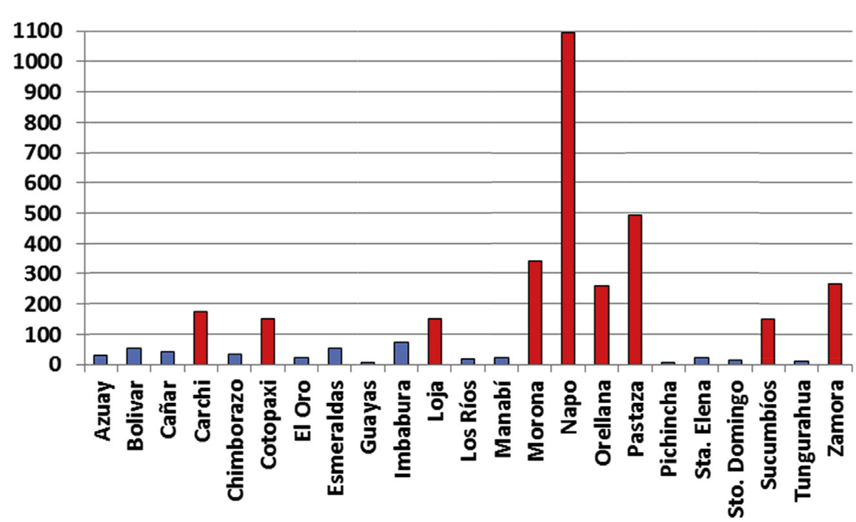

Fig. 12 – Percentage of replacing gasoline with H_2 by province.

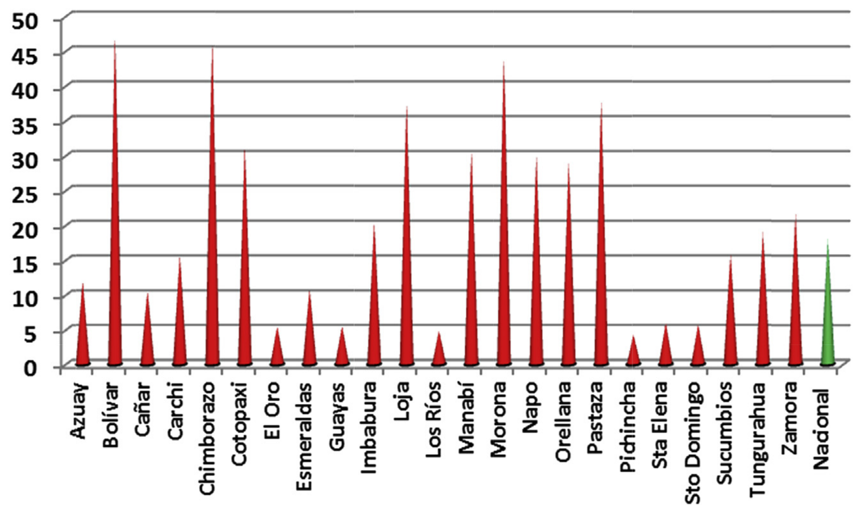

Fig. 13 – Percentage of rural households by province using firewood for cooking.

place in the same households. In that case, the remaining H_2 would meet this shortcoming in most provinces (20 out of 23), Fig. 15. The calculations are based on assuming an electricity consumption per capita in the same rural sector to 50% of consumption in the urban sector, 1137 kWh/year in 2010 [45], and a typical rural home is composed of 4 people [60]. While for the FC it is considered a PEMFC with an average efficiency of 50%, a value used in a study for a final similar use [61].

The end-use technologies of H_2 for both applications are known and commercially available, especially FC electricity generation on a small scale [4]. However, its adoption for specific situations requires a detailed technical and economic study, which support decision making and whose development is beyond the scope and purpose of this article.

Conclusions

A preliminary assessment of the potential H_2 production by electrolysis from the use of renewable electricity from solar PV, wind, geothermal and hydropower sources was performed in Ecuador. The H_2 energy conversion would have a total

Table 10 – Equivalent H_2 Production in excess (deficit) by province.

Province	Firewood consumption (kg/year)	Equivalent H_2 consumption. (kg/year)	H_2 production (kg/year)	Surplus H_2 (*deficit*) (kg/year)	Surplus H_2 percentage (*deficit*)
Azuay	2.63×10^7	3.76×10^6	1.89×10^7	1.51×10^7	80
Bolívar	4.07×10^7	5.81×10^6	4.48×10^6	-1.33×10^6	−30
Cañar	9.38×10^6	1.34×10^6	5.50×10^6	4.16×10^6	76
Carchi	8.63×10^6	1.23×10^6	2.20×10^7	2.07×10^7	94
Chimborazo	8.98×10^7	1.28×10^7	9.31×10^6	$-3{,}52 \times 10^6$	−38
Cotopaxi	5.70×10^7	8.14×10^6	4.33×10^7	3.52×10^7	81
El Oro	5.14×10^6	7.35×10^5	1.00×10^7	9.30×10^6	93
Esmeraldas	1.75×10^7	2.49×10^6	1.50×10^7	1.25×10^7	83
Guayas	2.10×10^7	2.99×10^6	1.59×10^7	1.30×10^7	81
Imbabura	2.45×10^7	3.50×10^6	2.00×10^7	1.65×10^7	83
Loja	5.05×10^7	7.22×10^6	4.00×10^7	3.28×10^7	82
Los Ríos	1.16×10^7	1.66×10^6	7.52×10^6	5.87×10^6	78
Manabí	1.18×10^8	1.68×10^7	1.82×10^7	1.42×10^6	8
Morona	2.33×10^7	3.33×10^6	2.36×10^7	2.02×10^7	86
Napo	1.03×10^7	1.47×10^6	6.68×10^7	6.54×10^7	98
Orellana	1.25×10^7	1.78×10^6	2.29×10^7	2.11×10^7	92
Pastaza	9.81×10^6	1.40×10^6	3.06×10^7	2.92×10^7	95
Pichincha	2.36×10^7	3.37×10^6	1.42×10^7	1.08×10^7	76
Santa Elena	5.14×10^6	7.34×10^5	3.80×10^6	3.06×10^6	81
Sto. Domingo	3.55×10^6	5.07×10^5	4.06×10^6	3.55×10^6	88
Sucumbíos	9.25×10^6	1.32×10^6	1.85×10^7	1.72×10^7	93
Tungurahua	4.00×10^7	5.72×10^6	3.84×10^6	$-1{,}88 \times 10^6$	−49
Zamora	6.90×10^6	9.85×10^5	1.06×10^7	9.61×10^6	91
Country	$\mathbf{6.24 \times 10^8}$	$\mathbf{8.91 \times 10^7}$	$\mathbf{4.31 \times 10^8}$	$\mathbf{3.42 \times 10^8}$	**79**

Figures in italics represent deficit.

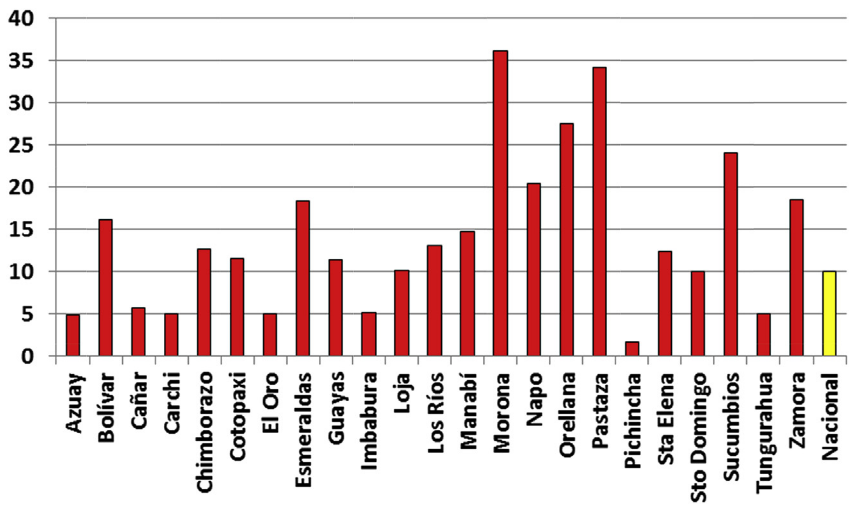

Fig. 14 – Percentage of rural households without electricity by province.

production of 4.55×10^8 kg/year for technical potential, where solar PV is the largest contributor. The subsequent use of H_2 focuses on two niche opportunities, automotive transportation and rural electrification, in both cases, the purpose is to replace inefficient sources of energy to a more efficient and less polluting energy carrier. In the first case, the nationwide replacement of gasoline and diesel by H_2, would exceed 50% of imported volumes. In the mainland provincial level, it is considered only the replacement of gasoline, achieving variable levels of replacement by province, reaching full replacement in 9 of the 23 provinces (39%), with favorable energy, environmental and economic consequences that this entails. In the second case, replacement of firewood by H_2 as a heat source for cooking in rural households occurs in 87% of the provinces. This case also suggests the use of H_2 excess in the supply of electricity in the rural households without this service, assuming that both the replacement of firewood by H_2 and the supply of electricity by FC would take place in the same households. However, this hypothetical scenario of a complementary use of H_2 should be subject to a statistical treatment to determine the validity of this assumption.

From the preliminary assessment of the potential of renewable production of electrolytic H_2 in Ecuador it is concluded that this vector could constitute a suitable mechanism for improving the quality of life of people, particularly in poor rural areas while contributing to a favorable change in the country's energy matrix. The incorporation of an efficient and suitable vector as a secondary power supply also means reducing consumption of imported liquid fossil fuels and the resulting environmental pollution. It is clear that the Republic of Ecuador provides interesting perspectives, from both the supply and demand, to advance in the incorporation of H_2 in its energy system. However, it is necessary to carry out more detailed studies in order to analyze the viability of both H_2 applications, especially in those provinces where the results indicate a high availability of H_2 and opportunities for its use. Finally, it is important to evaluate the production of H_2 from the existing bioenergy in the country in order to complete the

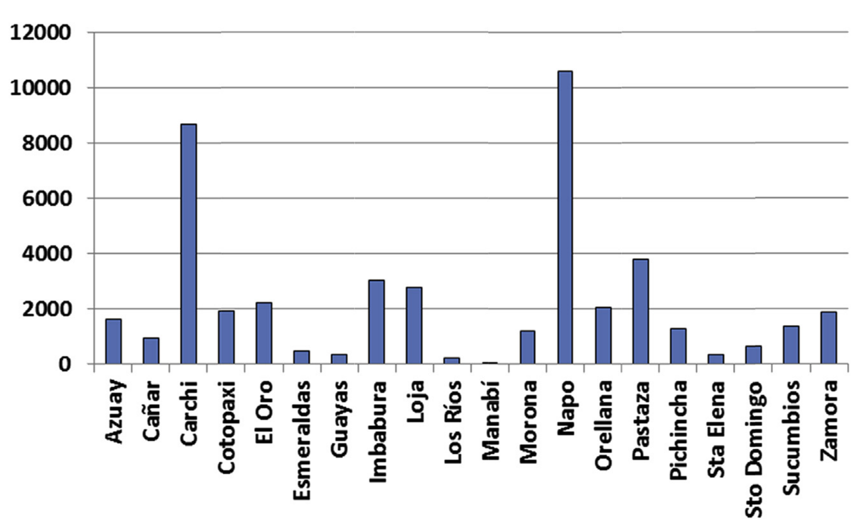

Fig. 15 – Percentage of electric power supply of H_2 FC in rural households by province.

preliminary study on the potential for producing renewable H_2 in Ecuador. This analysis will be the subject of a future paper.

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