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Hydrogen from hydropower in Ecuador: Use and impacts in the transport sector

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ABSTRACT

This paper estimates the potential for hydrogen production via electrolysis from hydropower coming from spilled turbinable energy of the hydroelectric plants of Ecuador. As a case study, the use of hydrogen in fuel cell-powered vehicles in public transportation in Cuenca city is analyzed. The technical and economic analysis determine the size of the electrolytic plant as well as the cost of hydrogen production, valued at 1.77 US$/kg in the best-case scenario. When compared to the price at which the State buys diesel in the international market, the results show that the cost of hydrogen is only 0.64 times the cost of diesel. In addition, the favorable impact of hydrogen penetration is calculated from both environmental and economic points of view. This study concludes that hydrogen production from untapped hydropower and its use in Cuenca's urban transport is a niche opportunity for leading the country towards a Hydrogen Economy.

Introduction

The disadvantages of the current energy system based on the use of fossil fuels are widely recognized. The most important drawbacks of the system are: the certainty of disappearance of fossil fuels in the medium term, making these sources unsustainable; their uneven geographical distribution, favors geopolitical conflicts causing the instability of the energy market causing a difficult energy planning and countries development; and environmental pollution mainly for the indiscriminate burning of these fuels. Today is necessary a deep conceptual and structural change in the way that human society uses the energy to meet its needs [1], It explains the renaissance of the use of renewable energy sources, highlighting that, in 2013 they accounted 19% of global energy consumption and 22% of electricity generation, with a global investment in the order of US $ 213 billion [2].

However, there are two limitations related to renewables energies – RE slowing its advance: the intermittence for harvesting them and the difficulty of storing their surplus. In this scenario Hydrogen (H_2) is emerging as a new energy vector that could contribute significantly to overcome these limitations, especially the second one by providing an appropriate and efficient mechanism to both storing and transporting energy [3]. Thus, in Solar-Hydrogen Energy System – SHES, RE

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Nomenclature

Acronyms
ARCONEL agency for regulation and control of electricity
BOE barrel of oil equivalent
CDM clean development mechanism
CELEC EP Strategic Public Enterprise Electric Corporation of Ecuador
CENACE National Center for Energy Management of Ecuador
CERs certified emission reductions
CONELEC National Electricity Council of Ecuador
EMOV EP Municipal Public Enterprise of Mobility, Traffic and Transportation of Cuenca
FC fuel cells
FCV fuel cell vehicles
GHG green house gases
HHV higher heating value
IDB Inter-American development bank
IPCC Intergovernmental panel on climate change
IRR internal rate of return
LPG liquid petroleum gas
NPV net present value
NREL national renewable energy laboratory
PEM proton exchange membrane
RE renewable energies
SHES solar-hydrogen energy system
SNI interconnected national system
VOCs volatile organic compounds
ZEV zero emissions vehicle

Parameters
CF capacity factor, adimensional
HHV H_2 high heat value, kWh/kg
Eo overall efficiency, adimensional
Fa availability factor, adimensional
ρ_{H2O} water density, kg/m^3
G gravity, m/s^2
FM management factor, dimensionless
R_{H2} performance of H_2 buses, kg/km
R_D performance of diesel buses, l/km
C_{UE} electrolyzer unit energy consumption, kWh/kg
T_w water tariff, US$/m^3
DI power plant availability, h
n life time period, year
d active interest rate, dimensionless
FRC capital recovery factor, dimensionless
OM O&M rate, dimensionless

Variables
STE spilled turbinable energy, MWh
P_{MHIDRO} mini-hydro potential, MW
E_{MHIDRO} mini-hydro electrical energy, MWh
P_{H2} annual production hydrogen, kg/year
E_{EXC} excess energy, J
V spilled volume, m^3
H height of the waterfall, m
D_{H2} traveled distance by vehicles powered by H_2, km/year
D_G traveled distance by vehicles powered by gasoline, km/year
D_S traveled distance by vehicles powered by diesel, km/year
R_{AB} annual distance traveled by the urban bus fleet, km
C_{EG} cost of electricity generation, kWh/kg
P_{H2V} annual H_2 production (volume), m^3/year
C_{AE} annual electricity consumption, kWh/year
C_{EG} cost of electricity generation, kWh/kg
C_E annual electricity cost, US$/year
C_w annual water consumption, m^3/year
C_{WATER} annual water cost, US$/year
C_{INS} annual input cost, US$/year
P power of electrolysis plant, MW
C_{EL} electrolyzer unit cost, $/kW
C_{IE} electrolyzer installation cost, $
C_{INV} annual investment cost, $/year
C_{OM} annual O&M cost, $/year
C_{TP} total production cost, $/kg H_2

are the primary sources and H_2 the secondary source, or energy carrier, it's being considered as an innovative energy structure, that could fully meet the society power needs by the middle of this century within the framework of the so-called Hydrogen Economy [4]. In the SHES, the H_2 is obtained from RE, and then stored, transported, distributed and produced through end-use technologies in which the chemical energy contained in H_2 is transformed to useful forms such as heat and electricity [5].

Among the several options to obtain H_2 in a SHES, electrolysis, the breaking of a water molecule by applying electricity, is one of the more efficient and less pollutant way, especially in the case of hydropower, where the generation cost is the key variable to be considered into the SHES′ total cost structure [6]. In this way, the H_2O electrolysis from hydroelectricity will be cost-effective where this energy source is abundant and cheap. It's no coincidence, that countries with large hydropower potential such as Canada, U.S.A., Brazil and Norway have undertaken ambitious development projects of SHES, by estimating their production capacity of electrolytic H_2. Similar studies also have been done in several Latin American countries. These experiences are shown below and the methods used for such estimations are described.

The H_2 estimation that could be obtained from the hydropower potential for a country or region has been done through two ways, without ruling out other methodological approaches that could be used. The first way is simply assume that a percentage of the economic hydropower potential available is used for the production of H_2 by electrolysis. Thus in Ref. [7] the potential production of electrolytic H_2 in Venezuela from different RE types is quantified and, in the case of hydropower, it is considered the potential of mini-hydro plants, defined as the generation capacity up to 50 MW per installation.

The second way of assessing the amount of H_2 obtainable from hydropower is based on the called hydroelectricity in excess or STE [8], understood as the power that could be generated from turbinable water that must be spilled due to: demand reduction or high values of inflow to the dam because of the season or operational reasons. The use of this excess energy to produce H_2 improves the capacity factor and the efficiency of the plant [9]. This form of renewable H_2 production has been studied in several countries being Brazil one of the pioneers, probably because its large hydroelectric potential estimated in 260 GW [10]. In this regard, in the northeast of Brazil was analyzed the production of electrolytic H_2 by the combination of solar and wind energy and hydroelectricity in excess. The volume of H_2 obtained, 56.26×10^6 m^3 H_2/year at a cost of 10.3 US$/kg, would be for export [11]. Similarly, an inventory of the amount of the spilled turbinable water from the 100 largest hydroelectric plants in the country was done concluding that the electricity that could be produced is 106 TWh, equivalent to 30% of total production in Brazil for year 2008. This water amount would produce 3.22×10^9 kg of H_2, assuming 33 kWh per kg of H_2 obtained, which would be used to power fuel cells for automotive use, avoiding the emission of 5.7×10^7 t CO_2/year [12].

A more specific study to quantify the surplus hydropower was conducted in order to determine the turbinable spilled water from Iguazú, the largest Brazilian dam. By considering the monthly average volume of spilled water, for a period of six years, the analysis obtained a maximum value of energy generation in excess of 1,054,899 MWh and a minimum of 9559 MWh. The most important result from the study indicates that energy demand to produce enough electrolytic H_2 to move the entire fleet of public transport in the city of Foz de Iguazú, was estimated between 1.5% and 8.5% of that energy in excess, it indicates the magnitude of the energy potential that is not used [8]. Similarly, in Paraguay it has been studied the H_2 production by using the STE from Iguazú dam (shared with Brazil). The study proposes H_2 to produce hydro-methane as a fuel for vehicles instead of natural gas [13]. This study is complemented by a recent paper published by the same authors consisting of a thermo-economic analysis of H_2 production from hydropower. This is a large scale analysis including storage and distribution toward supply stations for automotive transportation, emphasizing the option of hydro-methane as an alternate energy vector of H_2, in order to reduce the associated costs when implementing such infrastructure [14].

In Colombia the production of electrolytic H_2 has been analyzed from energy excess at the Amoyá hydroelectric plant, located in the center of the country, with the aim of providing energy, in the form of electricity and heat for meeting the needs of a hypothetical population of 16,000 inhabitants located near to the production site [15].

In North America, NREL has estimated the potential production of H_2 from renewable and nonrenewable sources [9,16]. In the case of hydropower it's considered that 30% of the annual electricity production generated from 1321 plants in the country can be considered excess hydropower. This energy might be directed to hydrogen production obtaining a value of 1×10^6 tonnes of H_2 for year 2006 [16]. In Canada it was proposed the production of H_2 by electrolysis from surplus hydropower in a plant located in the northwest of the country, with an average of 63% of idle capacity, resulting in a production between 4 and 7 tonnes of H_2 for day, depending on the system operation of the electrolysis plant [17].

Finally in Ecuador the production of H_2 by electrolysis from excess hydropower from the Paute-Molino power plant was analyzed, located in the south of the country, establishing the use of H_2 as an energy carrier and chemical feedstock for various industrial processes. The study suggested that 30% of the spilled water from the dam in year 2011 could be used to generate additional electricity for the production of H_2. The analysis considers two scenarios depending on the amount of turbinable water for H_2 production; the first assumes 30% of its annual total obtaining available energy in the order of 293.3 GWh/year, the second duplicates this amount reaching an annual H_2 production of 5400 t/year and 10,802 t/year, respectively. As a result, the capacity factor of the plant increases 5% and 10% for each scenario. The calculation is based on energy consumption by the electrolyzer of 52.3 kWh per kg of H_2 [18].

This review shows that H_2 production from hydroelectricity is an open topic within the SHES analysis and its potential use has attracted the interest, particularly in the Latin American region due to its enormous hydropower potential, placing H_2 as a sustainable and efficient alternative to meet the energy requirements in different sectors of society. However, after the analysis of the studies conducted so far it can be presumed that the percentage of usable spills included in the calculations are the product of rough estimates that do not show in detail both the historical behavior of such discharges and the actual percentage of availability for H_2 production. In that sense, the amount obtained in several cases might be largely overestimated. This article aims to overcome these methodological and procedure limitations by considering, for the proposed case of study, actual STE values for H_2 production.

In this context, the main purpose of this paper is to estimate the potential production of H_2 in Ecuador from the available STE in the country and its subsequent use in two geographical areas. The first one will cover the whole country whereas the second will analyze the Andean city of Cuenca, capital of Azuay province, located in the southern region. In the latter case, three penetration scenarios of the H_2 carrier are raised within the urban public transport depending on the level of demand coverage. Both environmental and economic impacts of such a penetration are also estimated, which allows assessing the role of this energy carrier as contributor to characterize Cuenca as a sustainable city in Latin America and incorporating Ecuador to the Hydrogen Economy. Finally, the study seeks to provide elements that can contribute to the transformation of the Ecuadorian energy matrix towards a structure dominated by RE.

Hydropower potential

Concept of hydropower potential

Hydropower is a type of RE that takes advantage of both kinetic and potential energy from water in order to produce electricity. Thus hydropower potential, i.e. the generating potential from hydropower, depends on the flow rate and the height gradient due to the difference between two water levels. These two variables will ultimately determine the exploitable potential and also the technology to use in a particular hydroelectric project.

Similar to other RE sources, hydropower potential is classified into theoretical, technical and economic. The first one is a measure of the available water resources in a river system for energy production. It assumes that all the water that drains into a course is capable of generating electricity in function of flow and height with 100% of efficiency. Theoretical potential is then a measure of the total hydraulic natural resources for energy production [19].

While theoretical potential represents a value hypothetically available, it is virtually unfeasible, largely by technical limitations to use it. Thus the technical potential arises which represents the amount of energy to be generated taking into account the turbinable flow and the gross height, and considering the existing conventional technologies. Meanwhile, the economic potential is that part of the technical potential that could really be put into service with economic feasibility taking into account the cost of the energy obtained and its relation to other forms of electricity generation [20].

Hydropower potential in Ecuador

Historically, Latin America has been a world front-runner in hydroelectricity generation and consumption, with a wide lead over various regions of the world. Even discounting Brazil's contribution, the average hydroelectric production in the region is more than twice the world average [10]. With regard to Ecuador, its hydroelectric potential is determined by the geomorphological conditions of the country, with the presence of the Andes from north to south, dividing the territory into two main sheds of water, called the Amazon basin and the Pacific basin. Theoretical hydropower potential is obtained from the combination of total average flow, calculated as 15,123 m^3/s, and the difference of height levels, obtaining a value of approximately 93.4 GW, equivalent to 615,175 GWh/year [21]. Meanwhile, in Ref. [22] it is stated that the country's hydroelectric potential is 91 GW for the theoretical potential; 31 GW for technical potential and 22 GW for economic potential; but without giving further details on these estimates.

Table 1 – Main hydropower plants in Ecuador.

Company	Power plant	Effective power (MW)
CELEC EP HIDROPAUTE	Paute-Molino	1100
	Paute-Mazar	170
CELEC EP HIDROAGOYAN	San Francisco	230
	Agoyán	156
	Pucará	73
CELEC EP HIDRONACION	Daule Peripa	213
	Baba	42
EE QUITO	Cumbayá	40
	Nayón	29.7
HIDROABANICO	Hidroabanico	37.5

A more representative indicator of the hydroelectric potential of a country would be the density of hydropower potential or relative theoretical potential, defined as the theoretical hydropower potential per area unit of the country. Regionally, Ecuador ranks sixth out of twenty countries, exhibiting a value of 0.62 GWh/km^2 [10].

From the economic potential identified for Ecuador, it is barely exploited around 10%, as the installed power capacity is 2245 MW by year 2013 [23], value achieved in 55 existing hydroelectric plants. Table 1 shows the ten largest plants, with a total effective capacity of 2054.2 MW [24].

If these plants are added to plants under construction or starting their operation, with public and private investment, it would have the addition of 3363 MW, which would increase the installed hydropower capacity to 5608 MW in 2018 [25]. This amount is equivalent to 25.5% of the economic hydropower potential, being left 16,392 MW to take advantage.

H_2 production from hydropower in Ecuador

The estimate of the amount of H_2 that could be obtained from Ecuador's hydroelectric potential can be done considering the two approaches outlined for other countries. In the first case, from the generation projects in different stages of development registered in CONELEC,[1] about 10% is mini-hydro type [25]; therefore, it is valid to assume that 10% of the economic hydroelectric untapped potential available is mini-hydro, such that:

$$P_{MHIDRO} = 16{,}392\ \text{MW} \times 0.1 = 1639.20\ \text{MW} \tag{1}$$

The electrical energy associated with this potential is calculated assuming its availability throughout the year and a capacity factor – CF equals to 57%, which is an average value resulting of the operation of Paute-Molino power plant in the period 2010–2014 [26], such that:

$$E_{MHIDRO} = 1639.2\ \text{MW} \times 8760\ \text{h} \times 0.57 = 8.18 \times 10^6\ \text{MWh} \tag{2}$$

For the calculation of H_2 to be produced from this amount of energy it must be estimated the power required by both the electrolyzer to break the molecule of H_2O and get H_2 and by auxiliary equipment, and further weight the losses of the whole production process. For this the HHV of H_2, equals to 39.4 kWh/kg, is used given an efficiency Eo of 75% from the electrolytic process and a factor Fa of 95% [6], as shown in Eq. (3):

$$P_{H_2} = \frac{\text{Emhidro} \times \text{Eo} \times \text{Fa}}{\text{HHV}} = 1.48 \times 10^8\ \text{kg}\ H_2/\text{year} \tag{3}$$

The second way of assessing the amount of H_2 to be obtained from hydroelectricity in Ecuador is based on using the STE of hydropower plants with dams under operation. The

[1] In January 2015 the "LEY ORGÁNICA DEL SERVICIO PÚBLICO DE ENERGÍA ELÉCTRICA" was issued in Ecuador. This new law creates ARCONEL instead of CONELEC.

country has four power plants with regulating reservoirs located in different river watersheds: Mazar dam, with a monthly flow regulation, responsible for regulating the income flow to Amaluza dam of the Paute-Molino plant, turning the latter into a reservoir of weekly regulation, which has raised the capacity factor of this plant. Another reservoir with a seasonal regulation is Daule-Peripa of Marcel Laniado hydroelectric plant, located in the Coastal province of Guayas. Although the main purpose of this dam is the management and control of irrigation and flooding in the upper basin of the Guayas River, its operation allows seasonal flow management to be used in the power generation of such a plant. The fourth one is Pucara hydroelectric plant, in the Andean province of Tungurahua that has associated the Pisayambo reservoir.

Methodologically, this study is based on processing the information related to spills from the four reservoirs identified. This information is available in annual reports by CENACE, and whose evolution in the period 2007–2013 is presented in Table 2 [26]. It has been preferred to manage the hydrological behavior of reservoirs in a given time period rather than in a specific year, because it's a better technical representation of such a behavior.

Additionally, in Fig. 1 the average spill of each reservoir and total spill are shown in the period 2007–2013, appreciating a high variability among reservoirs depending on their activity.

Also, in the aforementioned annual reports [27], the average annual levels of the reservoirs, during the analysis period are presented. However, for the purpose of this study it is more important to know both the maximum operation level of dams, which represents the limit height before dumping occurs, and the river outflow, understood as the height at which water is replenished to the river. Both quantities are measured as meters above sea level – m.a.s.l. (Table 3). The difference between the two levels represents the height of the waterfall, or head of water, which is the value to consider when calculating the energy excess.

Potential of H_2 production

Annual average case

From the information contained in Tables 2 and 3 related to the average value of spills and levels for each reservoir in the period of study, it is possible to obtain the amount of power available, by Ref. [12]:

$$E_{EXC} = \rho_{H20}\, g\, V\, H \quad (4)$$

Then, by applying Eq. (3) H_2 production is obtained (Table 4) assuming in the calculation that all the available energy is intended to this production. This is an unrealistic scenario knowing that the total spill volume does not always respond to a reduction in energy demand or availability of "lazy" generation units that could be enabled for H_2 production, but also depends on the operating conditions of SNI. However, this ideal situation can be considered as the reference scenario.

In order to have a reference framework of the H_2 production, represented by the average of the analysis period, Table 5 is presented taking into account that an accurate comparison is not possible because each of the studies was made for particular contexts, time and conditions.

It can be seen that although the H_2 production in Ecuador is the smallest one, its order of magnitude is agree with the country's size and its hydroelectric potential, measured in terms of the available energy in excess.

Monthly average case

An alternative to the previous approach is to calculate the H_2 amount for monthly average values during the period 2007–2013, taking into account that the amount of STE, and therefore the available energy, is highly dependent on both the hydrology and the month considered. Table 6 presents the average monthly values of the spills during the period of study.

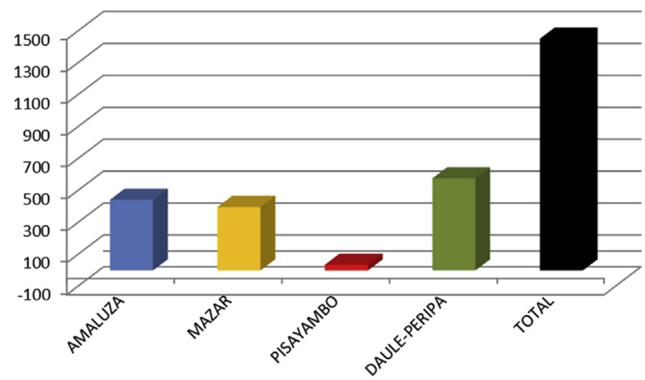

Fig. 1 – Average spills by dam and total spill ($m^3 \times 10^6$). Period 2007–2013.

Table 3 – Maximum and outflow levels in dams (m). Period 2007–2013.

	Amaluza	Mazar	Pisayambo	Daule Peripa
Maximum operation level	1991	2153	3569	85
Outflow level	1323	2007	3125	17

Table 2 – Annual spills by dam and total. Period 2007–2013 ($m^3 \times 10^6$).

	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 4 – Annual Hydrogen to be produced by dam and total. Period 2007–2013.

Year/Dam	AMALUZA	Mazar	PISAYAMBO	DAULE-PERIPA	Total (kg/year)
2007	2.54×10^7	–	0.00	0.00	**2.54×10^7**
2008	2.32×10^7	–	0.00	6.06×10^6	**2.93×10^7**
2009	1.25×10^7	–	0.00	0.00	**1.25×10^7**
2010	4.65×10^5	1.07×10^6	0.00	0.00	**1.54×10^6**
2011	2.56×10^7	5.15×10^6	1.84×10^4	6.67×10^5	**3.14×10^7**
2012	8.98×10^6	1.50×10^6	3.75×10^6	5.52×10^6	**1.97×10^7**
2013	5.90×10^6	3.72×10^6	1.63×10^2	1.29×10^6	**1.25×10^7**

Table 5 – Comparison between the H_2 to be produced in Ecuador and studies in other countries.

Country	H_2 (kg/year)	Year
Brazil [7]	3.22×10^9	2009
Venezuela [6]	7.14×10^8	2014
USA [10]	1.00×10^9	2009
This study (Ecuador)	1.25×10^7	2015

Applying the same procedure to calculate the H_2 production for the ideal scenario, the monthly values are obtained by reservoir (Table 7). Fig. 2 presents the total monthly production of H_2 appreciating that it varies between a minimum of 1.04×10^5 kg H_2/month (October) and 5.94×10^6 kg H_2/month (July). This behavior is because the final three months of the year correspond precisely to the period with fewer discharges due to seasonally, while the highest value in July corresponds to the rainy season, both on the coast and in the east, which implies a larger water volume in the tributaries of the reservoirs. This behavior will be crucial to evaluate the use of H_2 in the transport sector in selected geographical areas (see Table 8).

Final use of hydrogen

The chemical energy contained in the H_2 can be exploited in several ways: by combustion in internal combustion engines, burners or other similar device to produce mechanical power and heat; or by the electrochemical reaction in fuel cells for producing electricity. Furthermore, its use may be located in different sectors of the economy: residential, commercial, transportation, industrial. This study considers the potential use of H_2 in the transport sector, in vehicles being powered by fuel cells, whose characteristics and benefits have been extensively studied [28,29].

The transport sector in Ecuador

This sector of the economy is highly energy intensive, with a sustained upward trend in the last decade, representing as much as 49% in 2013 of the overall energy consumption in the country, equivalent to 48,551 kBOE. The percentage distribution of this consumption for 2013 is presented in Fig. 3, showing the wide prevalence of gasoline and diesel, while the use of electricity and LPG in this sector is marginal, 0.01% and 0.2% respectively, so that they are not represented herein.

The energy consumption in the transportation sector accounts for emissions to the atmosphere of 2.05×10^4 ktCO$_2$/year, representing 44.15% of total CO_2 emissions from Ecuador [23]. Besides the environmental implications, the progressive consumption in mobility based on fossil fuels has economic and social implications, as 100% of diesel and 65% of gasoline burned in the motor vehicle fleet are imported and then sold to consumers at subsidized prices. In this scenario any action to mitigate this great reliance on the use of oil derivatives and its adverse effects, would be fully justified.

The introduction of the H_2 carrier in the Ecuadorian transport sector

To study the penetration of H_2 in the transportation sector, the ideal hypothetical scenario is proposed, in which 100% of the spill volume from reservoirs is used for hydropower generation to H_2 production, as this scenario provides the highest use limit.

Table 6 – Average spills by dam and total average per month. Period 2007–2013 ($m^3 \times 10^6$).

	Amaluza	mazar	Pisayambo	Daule-Peripa	Average
January	6.03	17.89	2.07	0.00	**6.50**
February	19.48	0.00	2.44	0.00	**5.48**
March	8.00	0.67	2.96	213.91	**56.39**
April	50.05	14.40	2.56	167.79	**58.70**
May	56.19	41.77	3.55	60.06	**40.39**
June	117.85	50.02	2.80	47.26	**54.48**
July	141.62	210.06	4.09	75.59	**107.84**
August	45.30	54.15	5.88	11.99	**29.33**
September	14.06	13.17	4.79	0.00	**8.00**
October	0.52	0.05	3.32	0.00	**0.97**
November	16.19	2.44	0.75	0.00	**4.85**
December	6.46	11.30	0.00	0.00	**4.44**

Source [25].

Table 7 – Monthly average production of H_2 by dam (kg/month).

	Amaluza	Mazar	Pisayambo	Daule-Peripa
January	1.99×10^5	1.29×10^5	4.53×10^4	0.00
February	6.42×10^5	0.00	5.34×10^4	0.00
March	2.63×10^5	4.85×10^3	6.48×10^4	7.17×10^5
April	1.65×10^6	1.04×10^5	5.61×10^4	5.63×10^5
May	1.81×10^6	3.01×10^5	7.77×10^4	2.01×10^5
June	3.47×10^6	3.60×10^5	6.12×10^4	1.58×10^5
July	4.09×10^6	1.51×10^6	8.96×10^4	2.53×10^5
August	1.29×10^6	3.90×10^5	1.29×10^5	4.02×10^4
September	4.96×10^5	9.48×10^4	1.05×10^5	0.00
October	3.07×10^4	3.42×10^2	7.27×10^4	0.00
November	4.87×10^5	1.76×10^4	1.65×10^4	0.00
December	1.51×10^5	8.13×10^4	0.00	0.00
TOTAL DAM	**1.46×10^7**	**2.99×10^6**	**7.71×10^5**	**1.93×10^6**

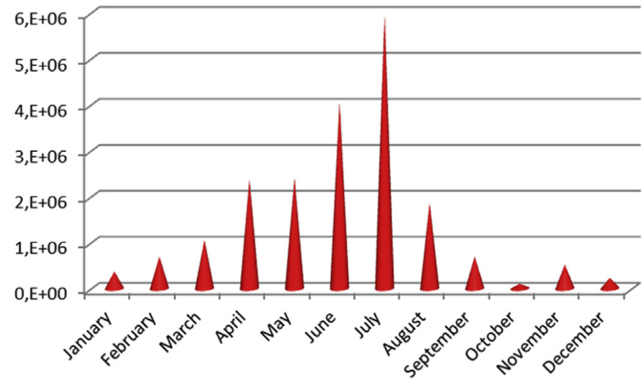

Fig. 2 – Monthly average production of H_2 in Ecuador (kg/month). Period 2007–2013.

The procedure to determine the feasibility of replacing gasoline and diesel by H_2 is based on determining the percentage of such a replacement and if it reaches appropriate values. For this, the annual distance traveled by vehicles powered by gasoline and diesel is estimated, and then compared to the distance to be traveled by vehicles using FC. This comparison is based on the consumption performance of the three fuels and on the H_2 production obtained from the surplus hydropower generation. For obtaining the density of mass and energy of the three fuels the values presented in Ref. [30] were used, while for each performance the values yields from Ref. [12] are considered. Calculations are done for 2013 as an annual case, whereas for the monthly case the average monthly values of the period of analysis were taken for the reasons already outlined, assuming a constant monthly value of gasoline and diesel consumption along the year, as obtained from Ref. [23].

For the annual case it can be noted that the H_2 produced covers only a fraction of the requirements of any of the two fuels consumed by the Ecuadorian fleet, even considering a hypothetical scenario of using 100% of spills for the H_2 production from hydropower, a percentage that is far from the real value of availability, as discussed later. Even if the option to satisfy only a percentage of the fleet is considered, the results would not be flattering to the intended use of H_2. In the monthly case, although the percentage of satisfaction increases, especially in the case of diesel, it is still low and has a broad monthly variability that makes it unlikely the substitution proposed at the national level. This leads to consider another scope in which the use of H_2 offers better prospects for viability and feasibility, by combining a localized demand with H_2 production close to it, where the end use might have significant implications in the selected area. That means a niche opportunity for using H_2 technologies in Ecuador, which encourages their gradual introduction in the transport sector and in the country's energy matrix. This approach is discussed below.

A contribution to sustainable transport: Cuenca case study

Cuenca: sustainable city of Ecuador

The motivation of this case study is directed to the end use of H_2 on public transportation in an urban area of the country in order to contribute to its sustainability. For this the Andean city of Cuenca, capital of Azuay province, southern Ecuador has been chosen. Cuenca is the country's third largest city with a population of 500,000 inhabitants approximately. Its geographical location is close to several hydroelectric plants, from where the energy to produce H_2 can be obtained with the aim to power FCV.

Cuenca is the only Ecuadorian city that belongs to the Latin America and the Caribbean Sustainable Cities Network. This is a community of 28 cities from 18 countries, sponsored by the IDB, through its Emerging and Sustainable Cities Initiative [31]. To qualify as a potentially sustainable city three dimensions are analyzed: environmental sustainability, urban sustainability and fiscal sustainability. These dimensions are represented by 144 performance indicators, from which Cuenca accomplishes fully 70, 37 indicators are partially achieved and 25 have negative evaluation [31]. Among the latter, with null accomplishment, it is the use of renewable energy sources in the automotive fleet, situation to which this study aims contributing to overcome.

An action designed to address mobility problems in a sustainable way and safeguard its architectural beauty

Table 8 – Percentage of gasoline and diesel to be substituted by H_2. Year 2013.

	D_{H2} (km/year)	Traveled distance (km/year)		Distance ratio (%)	
		Gasoline, D_G	Diesel, D_S	Gasoline D_{H2}/D_G	Diesel D_{H2}/D_S
Ideal Scenario	1.14×10^8	3.94×10^{10}	4.71×10^9	0.29	2.42

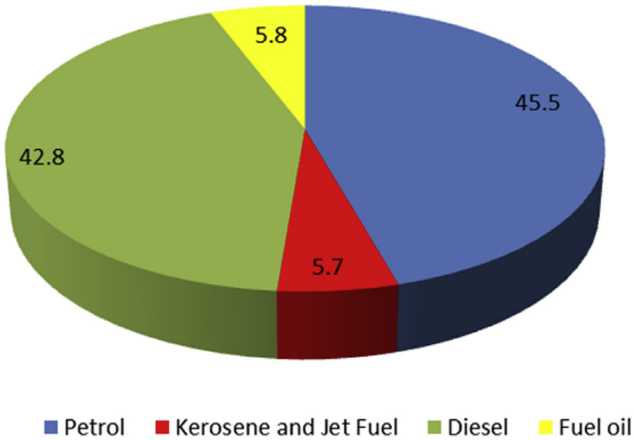

Fig. 3 – Percentage Distribution of energy consumption in the Transport sector (Ecuador) by type of fuel.

(Cuenca was declared a UNESCO World Cultural Heritage Site in 1999), is an important project called "Tram 4 Rivers". The tram, to be operational by mid-2016, will be the largest mass transit system of the city. Its investment exceeds US$ 232 million and will carry around 120,000 passengers per day [32]. The tram proposes getting articulated with other existing forms of mobility in the city such as walking, cycling, private vehicles and, of course, buses. Thus, complementarity between the tram and urban buses powered by alternative sources such as electricity or H_2-FC, which are environmentally friendly transport technologies, would largely guarantee meeting the needs for mass mobility of Cuenca's people in a sustainable way.

Available surplus hydropower

For the case study, the electricity required for the production of H_2 by electrolysis would be provided by the "Paute- Integral" Hydroelectric Complex, which consists of 2 plants in operation and 2 future plants. In its order, following the course of the Paute River, the first plant is Mazar, in operation since late 2010, with a 420 × 10^6 m^3 dam that allows a monthly regulation. Mazar has two power generation units at foot of dam, 85 MW of power per unit, for a total installed capacity of 170 MW.

The second hydropower plant, in operation since 1983, is Molino that has a smaller reservoir of 1 × 10^8 m^3, which allows a weekly regulation. This plant has 1100 MW of power thanks to 10 generation units and a large net height of water (660 m approximately, depending on the dam level).

The following plant is Sopladora, which approaches Molino's turbined flow through a direct interconnection. This project is under construction and its design power reaches 487 MW. It is planned to start its operation during the first semester of year 2016, so it will be considered in the present study. Finally, it is Cardenillo plant, whose final studies have been performed. This project will consist of a small dam with hourly regulation and an installed capacity of 590 MW. Since the project has not started its construction yet, Cardenillo will not be considered in this study.

The underlying concept of STE is that if a hydroelectric dam is spilling water from its reservoir, its production is not always at 100% of its installed capacity. There are various and very different causes for this condition. There are facilities that have limited infrastructure of the plant itself, the substation or the power transmission system. Other times, external situations to the plant might happen, for instance, the power system own conditions such as the low demand during the night or weekend, usually accompanied by forced generation close to major load centers in order to maintain operational conditions. Another common cause is that in situations where electric losses should be reduced or power system security must improve, distributed generation from several plants is preferred instead of increasing the power in a particular plant.

Whatever the cause, more water than strictly necessary is spilled, and thus the energy difference between the maximum capacity and the actually produced is wasted. This STE is not a direct proportion of the spilled volume but rather is site-specific as depends on the operating conditions of each plant. For the authors, this is one of the paper main contributions to several other studies consulted, as noted in the Introduction section (see Table 9).

In particular, Mazar and Molino power plants' operational regimes for the last four years have been studied (since Mazar came into full operation at the end of 2010). It has been found as a normal situation that, in spilling conditions, the plants works with less than the rated power during dawns, so there is a STE whose monthly average is presented in Table 10. This behavior is extensible to Sopladora power plant (when it started its operation), because it is a project without dam and its power depends on the flow rate from Molino. In other words, if Molino increases its energy then Sopladora's energy will increase accordingly.

It is important to note that the entry into operation in 2011 of Mazar, whose reservoir is four times larger than of Molino's dam and is located upstream of the latter, led to a sharp change in the operating regime of Molino power plant (higher capacity factor and lower discharges). For this reason henceforth the present study considers spills and other operating data for the years 2011 and beyond (Table 10), which may

Table 9 – Scenarios and percentages of gasoline and diesel to be substituted by H_2.

Month	Ideal scenario distance ratio (%)	
	D_{H2}/D_G	D_{H2}/D_S
January	0.10	0.86
February	0.19	1.61
March	0.29	2.43
April	0.66	5.49
May	0.66	5.54
June	1.12	9.36
July	1.64	13.75
August	0.51	4.29
September	0.19	1.61
October	0.03	0.24
November	0.14	1.21
December	0.06	0.54

Monthly average (2007–2013).

Table 10 – Actual monthly averages of available STE in Mazar, Molino, and Sopladora power plants. Period 2011–2014.

Month	Available STE (MWh) Mazar	Molino	Sopladora
January	364	672	299
February	–	–	–
March	250	6	3
April	169	6075	2706
May	80	1564	697
June	575	4012	1787
July	4186	31,001	13,810
August	1622	5455	2430
September	11	4264	1900
October	2689	1912	851
November	19	–	–
December	47	899	400
Total	10,013	55,859	24,731
% of the total spilled energy	**8.19%**	**11.91%**	–

Table 11 – Routes and travels of urban transport in Cuenca city.

Route number	Length of the round route (km)	Number of buses per route	Total daily travel (km)[a]
2	29.87	11	1642.85
3	37.00	20	3700.00
5	25.30	18	2277.00
6	48.60	12	2916.00
7	37.55	28	5257.00
8	33.15	20	3315.00
10	35.32	7	1236.20
12	36.21	18	3258.90
13	43.35	24	5202.00
14	25.34	19	2407.30
15	32.76	13	2129.40
16	43.45	19	4127.75
17	36.23	3	543.45
18	36.92	16	2953.60
19	27.58	14	1930.60
20	35.18	16	2814.40
22	27.34	30	4101.00
23	29.85	6	895.50
24	33.56	19	3188.20
25	24.30	6	729.00
26	39.81	10	1990.50
27	34.73	21	3646.65
28	39.85	23	4582.75
29	27.55	11	1515.25
Feeder 201	15.84	12	950.40
Feeder 203	12.46	12	747.60
North Trunk	23.50	20	2350.00
South Trunk	24.82	20	2482.00
TOTAL	**897.42**	**448**	**72,890.30**

[a] Considering a daily average of 5 tours per bus.

differ from the data presented for years prior the entry into operation of Mazar (Table 6).

The use of H_2 in Cuenca's urban bus fleet

For the analysis of this end-use of H_2 energy, three scenarios are proposed to replace gasoline and diesel used in vehicles with internal combustion engines for H_2 vehicles to be powered by FC, considering electrolytic H_2 from hydroelectricity. Such scenarios are defined by the percentage of replacing diesel buses in the urban fleet of Cuenca city, equal to 100%, 50% and 10%, and determining the level of satisfaction of each scenario.

In all cases, the amount of H_2 produced to supply buses equipped with FC, comes from the unused energy in Mazar, Molino, and Sopladora power plants, which would effectively be available for that purpose. This analysis is based on historical information of those plants and their dams, during the period 2011–2014, as presented in Table 10. It is important to note the average usable energy, while roughly corresponds to 11% of the STE, represents only 1% of the total energy produced and dispatched to SNI by those plants.

The fleet of public transport buses operating in Cuenca's urban area consists of 448 units, spread over 28 routes, representing approximately 4% of the total registered diesel vehicles in the city. Table 11 shows the routes and other operational characteristics of the buses fleet [33].

The annual distance traveled by the urban bus fleet, R_{AB}, equals to 26,240,508 km and was calculated assuming its operation during 360 days a year. With this figure and knowing the performance of H_2 buses, R_{H2}, as 0.10 kg/km [12,34,35], the amount of 2.62 million kg H_2/year would be required for that operation. To assess if this requirement can be satisfied with the production of H_2 obtained from the use of the STE from Molino, Mazar and Sopladora, the total available energy from these plants (Table 10) is taken into account, obtaining a value of 1.64×10^6 kg H_2/year. This amount of H_2 could meet 63% of the energy needs for the entire bus fleet of Cuenca.

A more precise estimate that represents better the actual situation consists on taking as baseline the average monthly production of H_2 from the plants already mentioned and uses the three scenarios for the demand analysis as shown in Table 12.

From the results of Table 11, it can be determined that the average satisfaction level for each scenario is 63%, 125%, and 625%, respectively. However this level is not homogeneous, but rather with large monthly changes as there are months with a production surplus and others with unmet demand, being the extreme case the month of February with zero demand met. Furthermore, as expected, by decreasing the H_2 monthly demand it is possible to cover a greater number of months per year with such an energy carrier (Fig. 4).

Another aspect to consider is the quantification of the monthly H_2 surplus or deficit for each scenario in order to undertake corrective actions that guarantee meeting the monthly demand. The values for each scenario are shown in Fig. 5(a, b, c). This information is complemented with the figures indicated in Table 13 for the three scenarios.

It is appreciated that none of the three scenarios can meet the H_2 demand for every month, whereupon two alternatives are proposed: 1) to buy the electricity needed to produce the H_2 during the deficit months at the value billed to large consumers; and 2) to store H_2 surplus of the corresponding months in order to use it in the months with H_2 deficit. The

Table 12 – Met Demand for the three substitution scenarios.

	Monthly production (kg)	Scenario 1 100% Demand		Scenario 2 50% Demand		Scenario 3 10% Demand	
		Demand H_2 (kg)	Meeting (%)	Demand H_2 (kg)	Meeting (%)	Demand H_2 (kg)	Meeting (%)
January	2.41×10^4	2.19×10^5	11.04	1.09×10^5	22.08	2.19×10^4	110.42
February	0.00	2.19×10^5	0.00	1.09×10^5	0.00	2.19×10^4	0.00
March	4.68×10^3	2.19×10^5	2.14	1.09×10^5	4.28	2.19×10^4	21.40
April	1.62×10^5	2.19×10^5	74.02	1.09×10^5	148.03	2.19×10^4	740.16
May	4.23×10^4	2.19×10^5	19.36	1.09×10^5	38.71	2.19×10^4	193.57
June	1.15×10^5	2.19×10^5	52.71	1.09×10^5	105.42	2.19×10^4	527.11
July	8.86×10^5	2.19×10^5	405.19	1.09×10^5	810.39	2.19×10^4	4051.93
August	1.72×10^5	2.19×10^5	78.62	1.09×10^5	157.24	2.19×10^4	786.21
September	1.12×10^5	2.19×10^5	51.06	1.09×10^5	102.12	2.19×10^4	510.62
October	9.86×10^4	2.19×10^5	45.09	1.09×10^5	90.18	2.19×10^4	450.91
November	3.44×10^2	2.19×10^5	0.16	1.09×10^5	0.31	2.19×10^4	1.57
December	2.43×10^4	2.19×10^5	11.13	1.09×10^5	22.27	2.19×10^4	111.33

second alternative, storing large volumes of H_2 for periods of several months, in addition to technological complexity, would increase significantly the costs. Furthermore, this alternative does not apply to the scenario one in which there is no full H_2 availability. Therefore, in order to have a preliminary estimate of the costs associated to H_2 production, the first alternative is proposed, taking into account the differential energy cost depending on the type of electricity used during the electrolysis process.

Cost model for using H_2 in Cuenca city's buses

Overview

For each of three scenarios, the model estimates the production cost for electrolysis H_2 from hydropower, based on the amount of H_2 required for the end use proposed. In that sense, this approach is conceptually a bottom up model. This type of method has been used in various technical and economic studies on H_2 production for different applications [12,36], and proceeds through the classification of annualized costs, input costs, investment costs, and operation and maintenance costs. Also similar economic studies are considered regarding the use of H_2 in urban transport in several cities: Asuncion in Paraguay [37]; Foz do Iguazú in Brazil [12]; London, England [38] and Madrid, Spain [39]. For H_2 production, a typical PEM electrolyzer was selected, with an average life of 15 years and

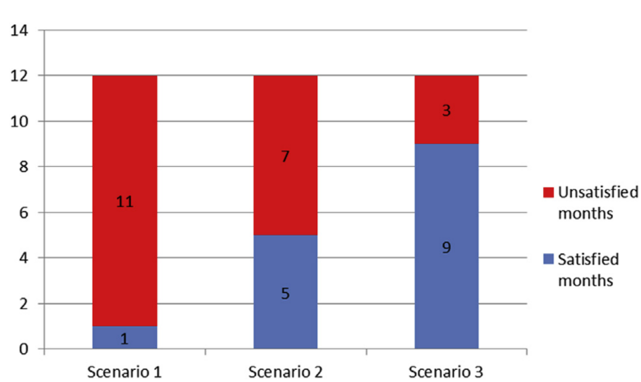

Fig. 4 – Months with met and unmet demand for each scenario.

a production capacity of 0.1–30 Nm^3/h [40]. This is the range at which H_2 production is estimated for the case study.

Input cost

Are included the costs of electricity and water needed to produce H_2 by electrolysis, which are obtained from the following expressions.

$$P_{H2} = F_M \times R_{AB} \times R_{H2} \tag{7}$$

In Eq. (7), F_M is a dimensionless parameter [36], which represents any losses in the operation of the electrolysis plant, with unit energy consumption, C_{UE}, equals to 52.53 kWh/kg H_2. This includes energy consumption by auxiliary equipment required for the treatment and compression of gases, and is equivalent to an energy efficiency conversion of 75%, which is an average value of those reported in the literature for the electrolytic system [12,36,38,40].

The annual energy consumption in this system is obtained as:

$$C_{AE} = P_{H2} \times C_{UE} \tag{8}$$

And the cost of electricity:

$$C_E = C_{AE} \times C_{EG} \tag{9}$$

Where C_{EG} represents the cost of electricity generation, which is composed of the cost of electricity in excess, estimated at US $ 0.011/kWh, and the cost established to large consumers, US$ 0.05/kWh. Both figures were supplied by the public company CELEC EP-Hidropaute, responsible for the operation of Molino and Mazar hydropower plants, and in charge of the construction of Sopladora [41]. So the cost of electricity will be a variable value depending on both the scenario and the month concerned, and from which the annual average value will be obtained to be used in Eq. (9).

To calculate the cost of water, source of H_2, the industrial rate of this input is used for Cuenca city, T_w, equals to 0.8 US$/$m^3$ [42], considering that 1 L of water is required to obtain 1 m^3 of H_2 [34,36], such that:

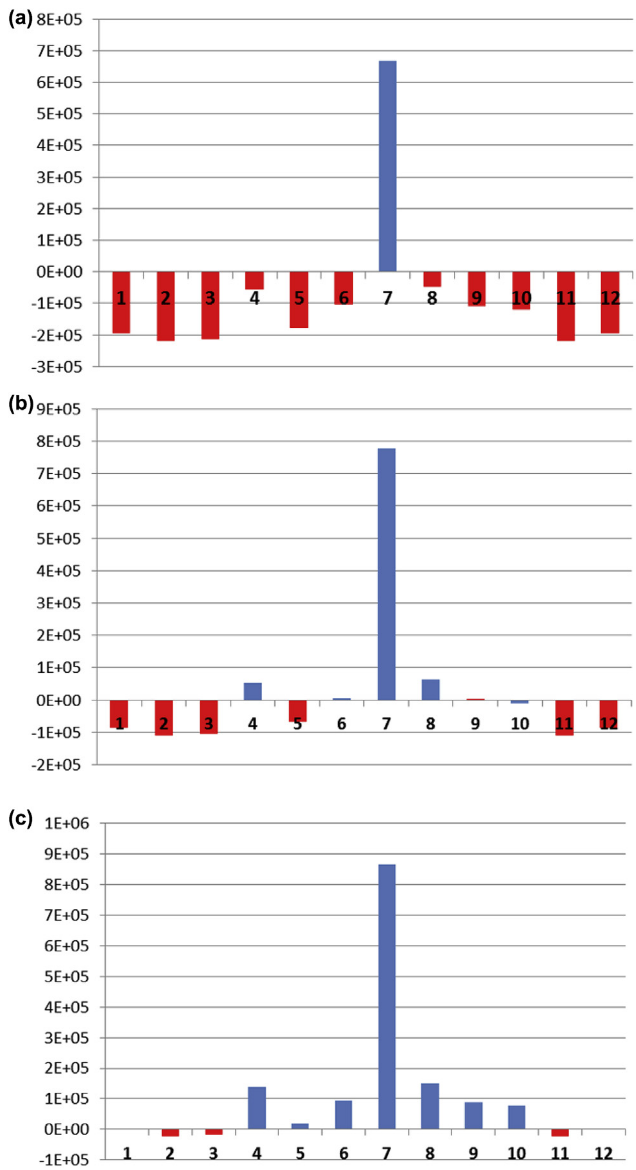

Fig. 5 – (a) Scenario 1. Monthly (lack or excess) of H_2. (b) Scenario 2. Monthly (lack or excess) of H_2. (c) Scenario 3. Monthly (lack or excess) of H_2.

$$C_{WATER} = C_w \times T_w \quad (10)$$

Where:

$$C_w = P_{H2V} \times 0.001\ m^3\ H_2O/1\ m^3\ H_2 \quad (11)$$

The equation for the annual cost of inputs is:

Table 13 – Relationship between lack and excess of H_2 production by scenario (kg/year).

	Scenario 1	Scenario 2	Scenario 3
Total monthly excess	6.67×10^5	9.00×10^5	1.44×10^6
Total monthly deficit	-1.65×10^6	-5.71×10^5	-6.06×10^4
H_2 net value	-9.83×10^5	3.29×10^5	1.38×10^6

$$C_{INS} = C_E + C_{WATER} \quad (12)$$

Cost of the electrolysis plant

It is represented mainly by the cost of the electrolyzer and ancillary equipment, and it is calculated from the energy needed to produce the required amount of H_2. First, the power plant is given by:

$$P = C_{AE}/DI \quad (13)$$

Where DI is the annual plant availability, equal to 8328 h/year, i.e. an availability of 95%. To represent the unit cost of the electrolyzer, C_{EL}, it is used the equation proposed in Refs. [36], obtained from a mathematical nonlinear regression procedure that takes into account the cost reduction due to economy of scale, and applicable for power values in plants between 5 MW and 30 MW. This expression is of the form:

$$C_{EL} = 1499.74 \times P^{-0.2167}\ R^2 = 0.987 \quad (14)$$

From (13) and (14), the cost of installing the electrolyzer and other additional equipment is calculated as:

$$C_{IE} = P \times C_{EL} \quad (15)$$

To calculate the annualized cost of investment in the life time of the installation, n, the expression of Capital Recovery Factor, FRC, is used for an average interest rate for investments in the industrial sector of Ecuador, d, for February 2015 [43]:

$$FRC = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (16)$$

Such that:

$$C_{INV} = C_{IE} \times FRC \quad (17)$$

Cost of operation and maintenance

In this case, it is assumed that the cost is simply a percentage of annualized investment costs, assessing the percentage of 5% [12,36,37], then:

Table 14 – Parameters of the cost model.

Parameter	Unit	Value
Water density	kg/m^3	1000
Gravity	m/s^2	9.8
H_2 high heat value	kWh/kg	39.4
Management factor	dimensionless	1.1
Annual distance traveled by buses	km	26,240,508
Performance of H_2 buses	kg/km	0.1
Performance of diesel buses	l/km	0.7
Electrolyzer unit energy consumption	kWh/kg	52.53
Water tariff	$US\$/m^3$	0.8
Plant availability	h	8328
Life time period	Year	15
Active interest rate	Dimensionless	10%
Capital Recovery Factor	Dimensionless	0,1315
O&M Rate	Dimensionless	5%

$$C_{OM} = OM \times C_{INV} \quad (18)$$

Total cost of H_2 production

The general expression for estimating the costs of H_2 production from hydropower related to the amount of H2 produced is:

$$CTP = \frac{CINS + CINV + COM}{P_{H_2}} \quad (19)$$

The parameters used in the cost model are shown in Table 14.

Results

The results of applying the cost model to the case of sustainable urban transport in Cuenca are presented in Table 15.

In Fig. 6 it can be seen that the input costs decrease when the rate of demand coverage falls, which can be explained by taking into account that such a reduction implies a greater contribution of low-cost electricity, from the STE, to the cost of inputs. Meanwhile, the cost of investment does not change because in all scenarios it is expected to produce the maximum amount of H_2.

The percentage distribution of costs according to their nature, for scenario one, shows the preponderance of the inputs cost (Fig. 7). This corroborates the importance of the electricity cost in the cost structure of H_2 production by electrolysis. In the scenarios two and three, inputs contribute with 67% and 60% of total costs, respectively, keeping the inputs primacy.

The results obtained in this study on sustainable mobility in Cuenca are compared with other studies for the same purpose in the cities referenced already (Table 16). Since each city has its specificities that do not allow a full comparison, the analysis is limited to noted that the cost of H_2 production obtained for Cuenca is favored by economies of scale and low cost of surplus hydropower.

Considering that 1 kg of H_2 equals to 14.12 L of liquid H_2, which in turn is energetically equivalent to 3.33 L of diesel [44], whose commercial value in Ecuador is about 0.29 US$/l [45], the resulting value of US$ 1.77 per kg of H_2 is 1.83 times the current cost (subsidized) of diesel Premium used in public transport in Cuenca. But if the comparison is done with the price at which the Ecuadorian State buys diesel in the international market, 0.84 US$/l [46], it results that the cost of H_2 is 0.64 times the cost of diesel. This means that use of H_2 in buses is economically competitive when considering the actual cost of diesel. In addition, the convenience of using this new energy carrier should take into account environmental and social effects of its use as well as the economic implications.

Environmental impact of using H_2 in CUENCA'S transport sector

This dimension of analysis of electrolytic H_2 production from hydropower in excess, evaluates the environmental implications of the H_2 use in fuel cell vehicles. The analysis focuses on the quantification of CO_2 emissions avoided, i.e. how a change of technology in the transport sector can contribute to mitigate the green house effect in Ecuador, specifically in the city of Cuenca.

In the global context, Ecuador is ranked 130 out of 232 countries in the statistics of annual CO_2 emissions per capita, with an amount of 2.07 t CO_2/person, value that also ranks Ecuador 13th among 29 countries in the Latin America and the Caribbean region [47]. Both countries rankings are a result of continued growth during the last 10 years of the GHG emissions, expressed in terms of $ktCO_2$ equivalents, with a significant contribution from the transport sector [23] as shown in Fig. 8.

The transportation sector is the main anthropogenic source of GHG emissions in Cuenca city. In year 2009, the total CO_2 emissions accounted 1074 kt/year, of which 59.4% corresponded to the transport sector, while the emissions contribution from diesel buses was 43,928 t/year, equivalent to 4.1% of the city total emissions [48].

The procedure for estimating the positive environmental impact of H_2 for vehicular use in Cuenca is to calculate the total volume of diesel burned by the fleet of buses taking into account its annual traveled distance as well as the

Table 15 – Results from the cost model for sustainable urban transport.

Variable	Unit	Value		
		Scen. 1 (100%)	Scen. 2 (50%)	Scen. 3 (10%)
Annual H_2 production (mass)	kg/year	2.62×10^6	2.62×106	2.62×10^6
Annual H_2 production (volume)	m^3/year	2.92×10^7	2.92×10^7	2.92×10^7
Annual electricity consumption	kWh/year	1.38×10^8	$1.38 \times$ E+08	1.38×10^8
Annual electricity cost	US$/year	4.90×10^6	3.82×10^6	2.76×10^6
Annual water consumption	m^3/year	2.92×10^4	2.92×10^4	2.92×10^4
Annual water cost	US$/year	2.34×10^4	2.34×10^4	2.34×10^4
Annual input cost	US$/year	4.90×10^6	3.82×10^6	2.76×10^6
Power of electrolysis plant	MW	16.55	16.55	16.55
Electrolyzer unit cost	$/kW	816.37	816.37	816.37
Electrolyzer installation cost	$	1.35×10^7	1.35×10^7	1.35×10^7
Annual investment cost	$/year	1.78×10^6	1.78×10^6	1.78×10^6
Annual O&M cost	$/year	8.88×10^4	8.88×10^4	8.88×10^4
Total production cost	$/kg H_2	2,59	2,18	1,77

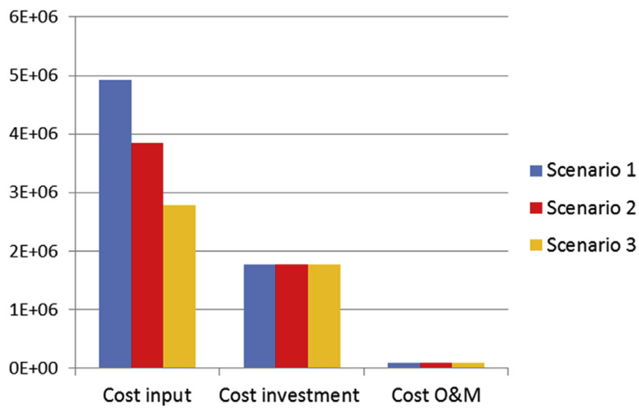

Fig. 6 – Cost variations under the scenarios analyzed.

performance of these vehicles, although the latter is very variable depending on vehicle operating conditions and age. Under these considerations, the value of 0.7 l/km was selected, which is very close to that used in Ref. [36] for a similar study. For the emissions calculation it is necessary to consider the combustion reaction of diesel. Regarding this aspect, the average structure of the hydrocarbon mixture component can be expressed by $C_{12}H_{23}$ in order to use it in calculations related to combustion [49], and whose reaction is:

$$4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O \quad (20)$$

From this information it is possible to obtain the amount of CO_2 emitted by diesel consumption in the bus fleet of Cuenca during year 2013 (Table 17).

The estimated annual production of CO_2 is compared to the values obtained using the parameters established by IPCC [50], obtaining similar amounts. The total CO_2 emissions, 48,300 tons, could be avoided by a complete replacement of the diesel bus fleet by another fleet based on H_2. Examples of environmental friendly performance of this type of vehicle are: the Honda Clarity, a passenger vehicle certified to the California Air Resources Board as a vehicle ZEV [51] and, with similar behavior of environmental friendliness, the bus Mercedes Benz Citaro Fuel Cell Hybrid, [52]. In both cases the byproducts of the electrochemical conversion of H_2 are water vapor and heat.

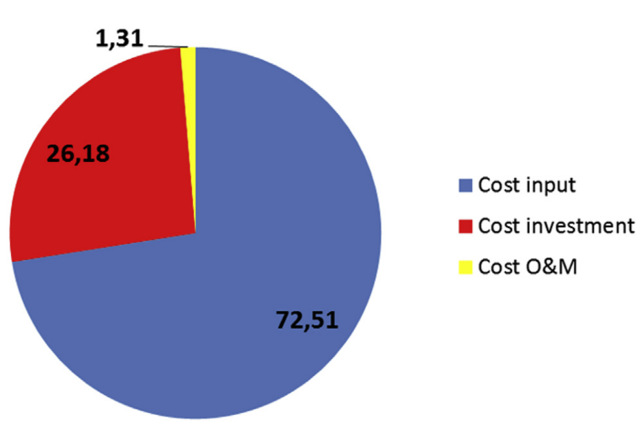

Fig. 7 – Percentage distribution of H_2 production costs. Scenario 1.

By replacing fossil fuels with H_2 in transportation, the emission of other pollutant gases such as sulfur and nitrogen oxides, particulate matter and VOCs, among others would be also avoided with positive effects on the air quality and human health. However, such an analysis is beyond the scope of this study, considering that CO_2 is the main component (about 99%) of GHGs generated by diesel vehicles.

Economic impact of using H_2 in the transport sector

In addition to the environmental implications, it is also important to evaluate the economic impact of massive use of H_2 in the transport sector, taking into consideration four ways of analysis. The first one estimates the costs associated with the removal of CO_2 emitted by fossil fuels combustion. This type of strategy to reduce the concentration of CO_2 in the atmosphere has attracted interest for its potential and scope, especially in developed countries that are the major contributors of these emissions [53]. The cost associated with the capture and confinement is strongly dependent on the origin of CO_2 emitted; i.e., the type of process and fuel. However, the value of 35 US$/t$CO_2$ has been reported as an average cost, excluding transport and storage [12,54,55]. Since the purpose of this study is to have an order of magnitude of the cost that would be avoided in a hypothetical scenario for removing CO_2 generated by the public transport in Cuenca, this will be the value used in the estimate. However, it is noteworthy that the widely distributed nature of GHG emissions in vehicles makes it difficult the practical implementation of this reduction strategy.

The second way uses the Carbon Certificates prices established in the carbon market, whose architecture has its origins in the Kyoto Protocol. This international agreement aims to reduce the cost of implementing actions to decrease GHG emissions based on certain market mechanisms. One of them is CDM, created to include developing countries in the carbon international stock markets. What is traded are CERs, or carbon credits, that represent the right to emit one ton of CO_2, and its value is determined by the law of supply and demand [56]. This study will rely on the value of the CERs market in London [57], equal to US$ 7.71 for the consultation date (13/02/2015). This value is used to calculate the market value of transport emissions in Ecuador, assuming the possibility of developing a CDM project.

The third way assesses the effect on the amount of subsidies provided by the Ecuadorian State to the use of fossil fuels in this sector of the economy, pointing out that 100% of the diesel used in the transport sector is imported and sold to the final consumer at lower prices than its international value [46]. Thus, the use of H_2 would mean the partial or total removal of subsidies with substantial savings for the State with the corresponding positive effects on the Ecuadorian economy.

The last way of analysis is to determine the monetary value of the number of oil barrels produced in Ecuador that would avoid their allocation for derivatives production and could be targeted for export, raising the income of the country in this area. The calculation is based on the premise that the diesel

Table 16 – Comparison with other cities for the same use of H_2.

City (energy source)	Number of buses	Cost of electricity (US$/kWh)	H_2 production (kg/year)	H_2 production cost (US$/kg)
Asunción, Paraguay (Hidropower)	55	0.037	2,750,000	4.32
Foz de Iguazú, Brazil (Hidropower)	191	0.0087[a]	2,996,000	(2.38–4.61)
London, UK (Public grid)	–	0.0525[b]	292,000	3.42
Madrid, Spain (PV, Public grid)	2	0.0864[c]	9125	9.61
Cuenca, Ecuador-Scen. 3 (Hidropower)	448	0.0200[a]	2,886,462	1.77

[a] Average value.
[b] For conversion: 1 £ = 1,5 US$.
[c] For conversion: 1€ = 1,2 US$.

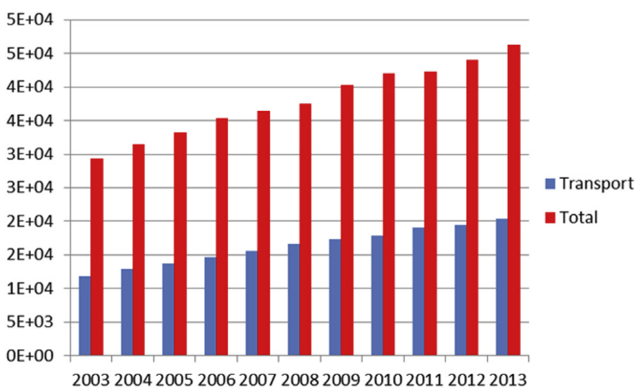

Fig. 8 – GHG Emissions in Ecuador: total and from transport sector (ktCO$_2$/year).

consumed in the bus fleet could come from domestic production. That is, the third pathway involves diesel import while the fourth one assumes its domestic production. In Table 18 there are presented the values in million US$ of the (positive) effect that would have the application of each of the pathways identified, for year 2013, and for each of the three scenarios considered.

Of the four pathways, way one is unlikely considering their technical implications. The ways two and three could be implemented in a complementary manner, although the way three might have more immediate effect. Finally, the favorable effect of the way four will depend on the oil price in the international market, which is characterized by high volatility making it difficult any economic projection thereof. Therefore it looks like option three is the most conducive to implementation.

To determine the cost/benefit ratio of Way Three, the total cost of H_2 production is considered for the three scenarios of analysis and then contrasted with the amount of subsidy that the Ecuadorian State would avoid to provide. This analysis yields values of 0.73; 1.23; and 4.99 for scenarios one, two and three, respectively. Even though the first scenario would be the most appropriate economically, when it is taken into account the need to have the H_2 infrastructure and the cultural impact that the introduction of a new technology for massive can mean, it is concluded that it would be appropriate to begin with the third scenario. This scenario includes the incorporation of 45 buses with FC-H_2 and greater use of STE, which is the primary purpose of the study. These buses would cover the routes that cross the historic downtown of Cuenca, contributing to its architectural preservation, mitigating the environmental pollution in the area and encouraging its touristic attractive.

In addition, it is worth to mention the collateral benefits of having large surpluses of H_2 for the last two scenarios quantified in Table 12, whose magnitude would be attractive to consider its commercialization to non-energy end uses such as medicine, food, petrochemicals, and upgrading oil. This criterion is also extensible to the O_2 produced, considering the stoichiometry ratio of the reaction of H_2 production: for each mole of H_2 it is also obtained 0.5 mol of O_2. A more detailed analysis of the demand and prices of both gases in Ecuador are outside the scope of this paper but, undoubtedly, if the mentioned substitution in transport is carried out then it will account for additional income that would favor the economic balance of such a replacement.

Finally, in order to understand the economic effect of introducing a new technology for public transportation in Cuenca, a comparison between H_2-FC buses and diesel buses was developed for 10% of the city fleet. The results of this exercise are presented in Table 19. It is important to note that the Discounted Pay Back Period is lower than six years and the Net Present Value (for an IRR of 10%) is close to $800,000.

Conclusions

The potential production of H_2 from hydropower in Ecuador has been estimated, considering the existing STE in four

Table 17 – CO_2 emissions by the bus fleet in Cuenca. Year 2013.

	Consumption[a] (l/year)	Consumption (mol/year)	CO_2 (mol/year)	CO_2 (kg/year)
Diesel	3.75×10^7	1.87×10^8	2.24×10^9	4.83×10^7

[a] Note: Estimate from annual total travel [31,46].

Table 18 – Economic implications of substituting fossil fuels (diesel) by H_2 (US$).

Scenario/Way	Way one CCC	Way two CER's	Way three Subsidies	Way four Export of BOE
Scenario 1	1.93×10^6	3.73×10^5	8.29×10^6	5.80×10^6
Scenario 2	8.46×10^5	1.86×10^5	4.14×10^6	2.90×10^6
Scenario 3	1.69×10^5	3.73×10^4	8.29×10^5	5.80×10^5

hydroelectric plants with reservoirs and focusing on the use of this energy carrier in the transport sector. At the national level it was obtained that, even in the best scenario, the H_2 production does not cover a significant percentage of the energy requirements of the entire fleet powered by gasoline and diesel. As a case study, Cuenca city was selected. The city is near to the Paute Hydropower Complex and from which the majority of the country' STE comes from. Through the combination, in different proportions, of the excess electricity cost and the value billed to large consumers it is possible to meet the need of 100%, 50% and 10% of the buses fleet in the city, with competitive production costs as compared to studies for other cities on the same vehicle end use of H_2.

Furthermore, the cost of H_2 production becomes 1.83 times the present cost (subsidized) of diesel Premium used in Cuenca's transport but if the comparison is done with the actual price at which the Ecuadorian State buys this fuel at the international market, it results that the cost of H_2 is 0.64 times the cost of diesel. This shows how economically competitive can become the H_2. Although the scenario of 100% coverage of the energy demand might be the best economically, the project proposed to Cuenca could be implemented in stages. Despite the energy potential for full coverage of the demand, aspects related to both infrastructure and costs should be studied in depth. For example, the location of the electrolysis plant, size of the storage system, the scheme of distribution and supply of H_2 (centralized or decentralized), the size of H2 bus fleet and their associated costs among others should be solve in advance. Although Table 19 shows some important parameters, a deeper economic analysis should be done in the future. Carrying out a full economic analysis is beyond the scope and extent of this study and will be conducted in a subsequent research. The energy-economic efficiency achieved at national level and particularly in Cuenca, along with the huge environmental and social benefits produced by this technological change, should be internalized in a more thorough analysis of the project, which makes the proposal promising in the near future.

Table 19 – Economic analysis of H_2-FC and diesel buses.

Variable	Unit	Value
H_2 bus investment (unit)	US$	1,500,000
Diesel bus investment (unit)	US$	200,000
Rescue value (on investment)	%	10
Life time period	Year	15
Inflation	%	3
Diesel cost	US$/gallon	2.8
H_2 cost	US$/Kg	1.77
Annual diesel cost	US$/year	738,015
Annual H_2 cost	US$/year	466,531
Annual fuel saving	US$/year	271,484
Internal rate of return	%	20
Net present value (10% of IRR)	US$	796,048
Pay back period	Year	5.53

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REFERENCES

[1] Muller-Steinhagen H, Nitsch J. The contribution of renewable energies to a sustainable energy economy. Process Saf Environ Prot 2005;83(B4):285–97.
[2] Renewables, Global status report. Web site: http://ren21.net, [accessed 14/02/2015].
[3] Winter C. Hydrogen energy, abundant, efficient, clean: a debate over the energy-system-of-change. Int J Hydrogen Energy 2009;34:S1–52.
[4] Bockris J. The hydrogen economy: its history. Int J Hydrogen Energy 2013;38:2579–88.
[5] Posso F, Sánchez J. La Economía del Hidrógeno en el Ecuador: oportunidades y barreras. Rev Av 2014;6:C46–62.
[6] Richa K, Buddhi D, Sawhney R. Comparison of environmental and economic aspects of various hydrogen production methods. Renew Sustain Energy Rev 2008;12:553–63.
[7] Posso F, Zambrano J. Estimation of electrolytic hydrogen production potential in Venezuela from renewable energies. Int J Hydrogen Energy 2014;39:11846–53.
[8] Riveros-Godoy G, Cavaliero C, Silva E. Analysis of electrolytic hydrogen production models and distribution modes for public urban transport: study case in Foz do Iguacu, Brazil. Int J Energy Res 2013;2013(37):1142–50.
[9] Milbrandt A, Mann M. Hydrogen resource assessment. Technical report. 2009. NREL/TP-560–42773.
[10] del Rubio M. TafunellX., Latin American hydropower: a century of uneven evolution. Renew Sustain Energy Rev 2014;38:323–34.
[11] Da Silva E, Marin A, Ferreira P, Camargo J, Apolinario F, Pinto C. Analysis of hydrogen production from combined photovoltaics, wind energy and secondary hydroelectricity supply in Brazil. Sol Energy 2005;78:670–7.
[12] Padilha J, da Trindade L, de Souza R, Miguel M. An evaluation of the potential of the use of wasted hydroelectric capacity to produce hydrogen to be used in fuel cells in order to decrease CO_2 emissions in Brazil. Int J Hydrogen Energy 2009;34:7898–902.
[13] Rivarolo M, Bellotti D, Mendieta A, Massardo A. Hydro-methane and methanol combined production from hydroelectricity and biomass: thermo-economic analysis in Paraguay. Energy Convers Manag 2014;79:74–84.
[14] Bellotti D, Rivarolo M, Magistri L, Massardo AF. Thermo-economic comparison of hydrogen and hydro-methane produced from hydroelectric energy for land transportation. Int J Hydrogen Energy 2015;40:2433–44.
[15] Carvajal H, Babativa J, Alonso J. Estudio sobre producción de H_2 con hidroelectricidad para una economía de hidrógeno en Colombia. Ing Compet 2012;12:31–42.

[16] Milbrandt A, Mann M. Potential for hydrogen production from key renewable resources in the United States. Technical Report. 2007. NREL/TP-640–41134.
[17] Oullette N, Rogner H, Scott D. Hydrogen form remote excess hydroelectricity. Part I: Production Plant and Production Costs 1995;2005(20):865–71.
[18] Pelaez M, Riveros G, Torres S, Garcia T, Albornoz E. Production and use of electrolytic hydrogen in Ecuador towards a low carbon economy. Energy 2014;64:626–31.
[19] Atlas del potencial hidroeléctrico del Perú. Web site: sigfoner.minem.gob.pe/hidro/Site/hgis/atlas/01_Atlas_texto.pdf. [accessed 16.02.15].
[20] Dimakis A, Biberacher M, Dominguez J, Fiorese G, Gadocha S, Gnansounou E, et al. Methods and tools to evaluate the availability of renewable energy sources. Renew Sustain Energy Rev 2011;15:1182–200.
[21] Estudio de Impacto Ambiental Definitivo Proyecto Hidroeléctrico COCA CODO SINCLAIR. COCASINCLAIR S.A. Web site: www.ecociencia.org/archivos/Antecedentes-110215.pdf [accessed 07.03.15].
[22] Orejuela V. Perspectivas de la matriz energética de electricidad en el Ecuador. La matriz energética del Ecuador, ESPOL; 2013.
[23] Balance Energético Nacional. Ministerio Coordinador de los Sectores Energéticos. 2014. Web site: www.sectoresestrategicos.gob.ec [accessed 01.03.15].
[24] Corporación Eléctrica del Ecuador, CELEC. Informe de Rendición de Cuentas, 2013. Web site: https://www.celec.gob.ec/images/2013.pdf [accessed 01.03.15].
[25] Consejo Nacional de Electricidad, CONELEC. Proyectos de Generación Hidroeléctrica. Web site: https://www.conelec.gob.ec [accessed 05.03.15].
[26] CELEC EP-Hidropaute Web site: http://hpaforms.celec.gob.ec/hidropaute/graficaproduccion/default.aspx [accessed 05.08.15].
[27] Centro Nacional de Control de Energía del Ecuador CENACE. Informe Anual 2013. Web site: http://www.cenace.org.ec/ [accessed 07.03.15].
[28] Yeh S, Loughlin D, Shay C, Gage C. An Integrated assessment of the impacts of hydrogen economy on transportation, energy use, and air emissions. Proc IEEE 2006;94:1838–51.
[29] Pollet B, Staffell I, Shang J, Molkov V. Fuel-cell (hydrogen) electric hybrid vehicles. In: Richard F, editor. Alternative fuels and Advanced vehicle technologies for Improved environmental performance. Wood head publishing Series in energy. Elsevier Science; 2014. p. 685–735.
[30] Boudries R. Hydrogen as a fuel in the transport sector in Algeria. Int J Hydrogen Energy 2014;39:15215–23.
[31] Cuenca: ciudad sostenible-Plan de acción. BID. 2014. Web site: http://issuu.com/cuencainternacional/docs/1_cuenca_ciudad_sostenible.compress [accessed 15.03.15], 345–389.
[32] Tranvía Cuatro Ríos. Web site: http://www.consorcio4rios.com/ [accessed 15.03.15].
[33] Dirección Municipal de Transito, DMT-GAD Cuenca Recorrido de buses urbanos Cuenca 2013. Web site: http://www.cuenca.gov.ec/ [accessed 16.03.15].
[34] Hua T, Ahluwalia R, Eudy L, Singer G, Jermer B, Asselin-Miller N, et al. Status of hydrogen fuel cell electric buses worldwide. J Power Sources 2014;269:975–93.
[35] Hydrogen Fuel Cell Buses: An economic assessment. Web site: http://www.ceem.unsw.edu.au/sites/default/files/uploads/publications/OwenandCockcroft.pdf [accessed 16.03.15].
[36] Contreras A, Posso F, Veziroglu T. Modeling and simulation of the production of hydrogen using hydroelectricity in Venezuela. Int J Hydrogen Energy 2007;32:1229–34.
[37] Galeano M, Peres da Silva E, Camargo J. Are HFC buses a feasible alternative for urban transportation in Paraguay? Int J Hydrogen Energy 2012;37:16177–85.
[38] Shayegan S, Pearson P, Hart D. Analysis of the cost of hydrogen infrastructure for buses in London. J. Power Sour 2006;157:862–74.
[39] Vidueira J, Contreras A, Veziroglu T. PV autonomous installation to produce hydrogen via electrolysis, and its use in FC buses. Int. J Hydrogen Energy 2003;28:927–37.
[40] Bhandari R, Trudewind C, Zapp P. Life cycle assessment of hydrogen production via electrolysis- a review. J Clean Prod 2013;85:151–63.
[41] Ing Juan Chávez, Subgerente de Producción de CELEC EP-Hidropaute. Personal interview, date: 29/03/2015.
[42] Web site: http://www.etapa.net.ec/Productos-y-servicios/Agua-potable/Operacion-y-Mantenimiento/Tarifas [accessed 21.03.15].
[43] Banco Central de Ecuador. Web site: http://contenido.bce.fin.ec/docs.php/documentos/Estadisticas/SectorMonFin/TasasInteres.html.
[44] Los Números del Hidrógeno. Web site: http://aeh2.org/ [accessed 21.03.15].
[45] Web site: http://es.globalpetrolprices.com/diesel_prices/#Ecuador [accessed 22.03.15].
[46] Banco Central de Ecuador. Ingresos y egresos: comercialización interna de derivados importados. Web site: http://www.bce.fin.ec/index.php/informacion-estadistica [accessed 05.04.15].
[47] Banco mundial: emisiones de CO2. Web site: datos.bancomundial.org/indicador/EN.ATM.CO2E.PC [accessed 05.04.15].
[48] Inventario de Emisiones Atmosféricas del Cantón Cuenca. Web site: http://cga.cuenca.gob.ec/Default_files/Documentos/informecalidaddeaire2011.pdf [accessed 05.04.15].
[49] Web site: http://www.newton.dep.anl.gov/askasci/chem07/chem07490.htm [accessed 09.04.15].
[50] IPCC. Climate Change 2014. Mitigation of climate change. Web site: http://www.ipcc.ch/report/ar5/wg3/[accessed 12.04.15].
[51] Web site: http://automobiles.honda.com/fcx-clarity/ [accessed 12.04.15].
[52] Web site: http://www.fuel-cell-e-mobility.com/technology/vehicles/citaro-fuelcell-en/[accessed 12.04.15].
[53] IPCC. Special report on carbon dioxide capture and storage. Web site: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf [accessed 15.04.15].
[54] Leung D, Caramanna G, Maroto-Valer M. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev 2014;39:426–43.
[55] The Global Status of CCS/2014. Global CCS Institute. Web site: http://www.globalccsinstitute.com/in-focus/global-status-ccs-2014 [accessed 25.04.15].
[56] Posso F, Acevedo J, Hernández J. El impacto económico de las energías renovables. AiBi Rev Investig Adm ingeniería-UDES 2014;2:49–54.
[57] Emisiones de carbón históricos. Web site: http://es.investing.com/commodities/carbon-emissions-historical-data [accessed 25.04.15].