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Hydrogen capacity for use in public transportation using the excess electricity generated by photovoltaics from rooftops in the urban area of Cuenca, Ecuador

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Abstract

The drawback of renewable technologies is the lack of coupling with energy demand, to reduce these drawbacks is by applying hydrogen as an energy vector. Hydrogen obtained from renewable energy sources could be stored and used when required, directly or in fuel cells. This work focuses on determining the hydrogen potential that can be obtained using photovoltaic plants in urban areas. In the city of Cuenca, with the renewal of the public transport vehicle fleet, it was reduced to 475 units, which emit 112 tons of CO_2 and burn 11,175 gallons of diesel per day. The analysis determines the photovoltaic energy that is produced by implementing photovoltaic panels in the Historic Center of Cuenca, Ecuador. With this it is determined that the electrical energy produced is 5.5 times the demand of the study area. With the energy surplus, it was determined that energy would be available that would cover between 97% and 127% of the demand required to mobilize the total urban buses. There are advantages such as the reduction of emissions or the increase in the quality of life, but the economic and technological aspects could be barriers to the implementation of these in the medium or short term.

Key words

Renewable energies, hydrogen, energy vector, photovoltaic solar energy, fuel cells, environment.

1. Introduction

During the last few years, the efficient use of resources as energy has become very important [1] [3]. In the face of increasing pressure on fossil fuels and oil prices, fossil fuels will continue to be the basis of global economic development [2] [4]. Cities must consider new supply options to meet their needs and ensure their resiliency without the resources to maintain and upgrade [5] [6]. This project analyses the impact of replacing conventional public transport with vehicles powered by hydrogen produced by electricity from photovoltaic solar systems placed in urban areas. The case in the historic center of Cuenca (Ecuador) has been analysed. The objective is to determine how much energy can be obtained from photovoltaic solar panels. Then, the energy storage potential is estimated through the production of hydrogen (H_2) from renewable energies (RE). Finally, a comparison of the data obtained with the current data of public transport in the city is made.

2. Methodology

The study area is delimited with the geographic information obtained from [7]. Then the radiation of usable energy is estimated and with the help of reduction factors that consider, among others, the efficiency, architecture, inclination or orientation, the technical potential is established. Once this potential is defined, the possible production of hydrogen by electrolysis is analysed. Finally, it is established whether the hydrogen produced would allow the substitution of public transport vehicles.

B Potential of photovoltaic solar energy in urban Cuenca

A certain area is selected to define the energy capture on the roofs. The information collected by Urgilés et al. [7] is used to delimit the study area, for which the INEC (Instituto Nacional de Estadística y Censos) divides the City of Cuenca into 80 census zones. Since the urban morphology of Cuenca makes the roofs have different slopes and orientations, in this work the study area has been delimited for the Historic Center of the City. This area comprises 2.58 km^2 corresponding to the 10 census zones. The survey carried out by Urgilés et al. [7] which corresponds to 20% of the homes in each census zone, which gives us an area of 0.288 km^2 to obtain 100%, the following equation is applied:

$$\text{Total roof area by census} = \frac{\text{(Estimated roof area)}}{\text{(\% representativeness)}} * 100 \quad (1)$$

This allows us to estimate an area of 1.55 km^2, which corresponds to the total of the roofs of the dwellings of the 10 chosen census zones.

B Estimation of usable solar energy

To estimate the amount of H_2 from photovoltaic technology, it is necessary to consider the values of solar irradiation in the city of Cuenca, which are obtained from the PVGIS database. Theoretically, in Cuenca (2,9 º Lat S) the irradiation is maximized when the orientation of the photovoltaic modules towards north, but, with a reduced slope of the collector surface (between 3 and 4%) , as consequence of the equatorial location, there is high irradiation level availability at any orientation setting [8].

C Technical Potential

The annual solar technical potential can be calculated using the equation [8]:

$$P= A_{FV} * I * Fr * n_r \quad (2)$$

Where:

P is the technical potential in kWh/year.
A_{FV} is the area available for installation on the ceilings in m^2.
I is the annual mean global irradiance in kWh/m^2.
Fr is the correction for architectural availability.
n_r the photovoltaic conversion for technological efficiency.

The average annual irradiation equal to 1528.51 kWh/m^2, according to the study [9]. Reduction factors (*Fr*) correspond to restrictions on the location of photovoltaic power based on architectural space availability and solar potential. In addition, the reduction factors (n_r) are included, which are the photovoltaic efficiency considering inverters, environmental conditions and dirt, which can affect the temperature of the cells and their efficiency. A set of reduction factors is applied to establish *Fr*, according to the following equation [8]:

$$Fr= C_{con} * C_{prot} * C_{so} * C_{or} * C_{in} * C_{SM} * C_{FV} * C_{ST} \quad (3)$$

This equation results on a 0.62 value, accordingly to values detailed in Table I.

Table I. The utilization factors used to calculate the available roof area.

Reduction factors	Value	Source
C_{con}	0,9	[10]
C_{prot}	1	[11]
C_{so}	0,8	[12]
C_{or}	0,96	[9]
C_{in}	0,9	[9]
C_{SM}	1	[13], [14]
C_{FV}	1	[15]
C_{ST}	1	
F_R	0,62	Equation 3

The technical potential reduction factors were considered also, factors that intervene in the conversion of irradiation into photovoltaic electricity. This were applied as reduction factors using the following equation [8]:

$$n_r=n_{ef} * PR \quad (4)$$

Where:
n_r is the solar potential reduction factor.
PR is the performance factor of the photovoltaic plants, considering losses due to dirt, wiring, dispersion, reflectance, shadows, transformers, orientation and inclination in consequences to architectural restrictions. In consequence a *PR*=0.76 reduction has been established.
n_{ef} is the photovoltaic efficiency. According to [16], this gives a result of an efficiency of 19% for monocrystalline modules, which gives us n_{ef} =0.19.

Therefore n_r =0,14 in order to calculate the technical potential of the study area of the city of Cuenca.

The power potential of the photovoltaic technology in the complete urban area is:

$$P= A_{FV} * I * Fr * n_r \quad (5)$$

$$P= 1.553.362,58\ m^2 * 1528,51\ kWh/m^2 * 0,62 * 0,14$$

$$P= 212.974.784,51\ kWh= 212,97\ GWh$$

In 2020, the electrical energy consumption in the same urban area of the city of Cuenca, was 38,366,701.47 kWh, data provided by the utility CENTROSUR [17].

In consequence, surpluses E_{PV} are calculated using the following equation:

$$E_{PV} = P - \text{Total energy consumption} \quad (6)$$

$$E_{PV} =212.974.784,51\ kWh- 38.366.701,47\ kWh$$

$$E_{PV} =174.608.095,04\ kWh= 174,61\ GWh$$

Accordingly, to this, the technical potential of photovoltaic solar energy is 5.5 times higher than the electrical energy consumed in the year 2020.

D Production of H_2 from photovoltaic exceeding's

With the availability of electrical energy, the production of H_2, by electrolysis, is defined. In Table 2 it can see the characteristics of a PEM (proton polymeric membrane) electrolyser. Table II shows the characteristics of a PEM electrolyser, with an efficiency, η_e, of 75%, and with a higher calorific value of H_2 of 141.86 MJ/kg (39.406 kWh/kg) [18], which includes the gas intake and purification systems, control systems and auxiliary equipment.

Table II. H_2 production in the City of Cuenca in 2015

PV Hydrogen Production		
Surplus	174.608.095,04	kWh
n_e	0,75	%
F_D	0,95	%
HHV Sup	39,406	kWh/kg
P H_2	3.157.125,08	kg

Finally, an availability of the electrolysis system, FD (availability factor), of 95% is assumed.

The equation to determine the amount of H_2 is as follows:

$$P_{H2} = \frac{E_{PV}*n_e*F_D}{HHV} \qquad (7)$$

$$P_{H2} = \frac{(174.608.095,04\ kWh*0,75*0,95)}{39,406\ kWh/kg}$$

$$P_{H2} = 3.158125,08\ kg\ H_2/year$$

The photovoltaic hydrogen produced from exceeding's, potentially reaches 3.157.125,08 kg

3. Results

A End uses of H_2 Proposal

The use of H_2 in the transport sector with the application of fuel cells is proposed, this is by far the top energy requirement in Cuenca (Figure 1) [15].

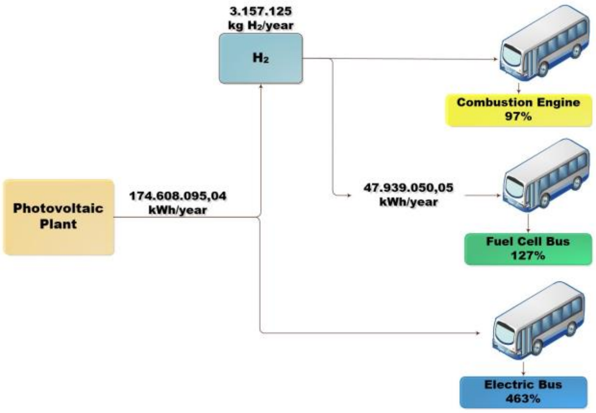

Fig 1. Analysis cases

B Hydrogen buses

To carry out the analysis of energy consumption of public transport in the city of Cuenca. The average distance travelled by a diesel bus is considered to be 68,654 km/year (188.09 km/day). The vehicle fleet travels around 32,610,650 km/year, knowing the performance of H_2 buses as 0.1 kg/km [19], 3,261,065 kg H_2/year is necessary.

In this way, it is established that the amount of hydrogen available covers 97% of the demand that a vehicle fleet that uses H_2 would require to cover the same annual route.

C Fuel cells

For the final use of H_2 analysis, it has been proposed to replace the diesel currently used for internal combustion buses with H_2-based buses to be powered by fuel cells. The capability of H_2 to supply the buses with fuel cells comes from the surpluses generated from photovoltaic solar energy installed on the roofs of homes in the Historic Centre of the city.

The energy value of hydrogen is $E_{H2\text{-}spec}$=39,44 kWh/kg [20], the chemical conversion efficiency is 37% at 40% of maximum rated power. For the calculations, an average efficiency of n_{Fc}=38,5% will be used [21]. In this way the amount of energy from the available hydrogen is given by:

$$\text{Total Energy}_{PEM} = P_{H2} * E_{H2\text{-}spec} \qquad (8)$$

$$\text{Total Energy}_{PEM} = (3.158125,08\ kg\ H_2/year) *(39,44\ kWh/kg\ H_2)$$

$$\text{Total Energy}_{PEM} = 124.518.013,16\ kWh/year$$

Then the electrical energy available with the fuel cells will be:

$$\text{Electric power available} = \text{Total Energy}_{PEM} *n_{FC} \qquad (9)$$

$$\text{Electric power available} = 124.518.013,16\ kWh/year *0,385$$

$$\text{Electric power available} = 47.039.050,06\ kWh$$

If it is considered that the amount of energy required to mobilize an electric bus is between 0.81 km/kWh [22] or 0.93 km/kWh [23] (the average 0.865 km /kWh), the distance to be traveled can be estimated with the amount of energy available:

$$\text{Distance} = \text{Electric power available*Bus performance} \qquad (10)$$

$$\text{Distance} = 47.939.050,06\ kWh * 0,865\ km/kWh$$

$$\text{Distance} = 38.830.630,55\ km$$

Since the vehicle fleet travels around 32,610,650 km/year, the available energy could cover 127% of the vehicle fleet's journey

D Direct use of electrical energy

From the surpluses generated on the roofs of the Historic Center of Cuenca, around 174,608,095.04 kWh (174.61 GWh) can be obtained and knowing that the performance of electric buses is 0.865 km/kWh [22], [23], the total distance of available energy can be estimated from:

$$\text{Distance} = \text{Electric power available*Bus performance} \qquad (11)$$

$$\text{Distance} = 174.608.095,04\ kWh * 0,865\ km/kWh$$

$$\text{Distance} = 151.036.002,21\ km$$

Considering the total distance demanded 32,610,650.00 km, it is established that 463% of the route of the vehicle fleet can be covered.

4. Implications

A Environmental implications

The environmental analysis focuses on quantifying the CO_2 emissions avoided by changing the technology used for public transportation. In 2014 the total CO_2 emissions reached 1,372,434t/year, of which 801,285.9 t/year, equivalent to 58.4% corresponds to the transport sector, the emissions from diesel buses were about 5.6% of the total emissions from the transport sector [24].

To estimate the positive environmental impact of the use of H_2 for use in the vehicle fleet in Cuenca, the overall volume of diesel consumed has been established considering the distance travelled in 2020.

Under these considerations, the value of 0.175 lt/km was taken [24], with these values it is possible to determine the amount of CO_2 generated by the consumption of diesel in the buses of the city of Cuenca, throughout the year the buses travel 32,610,650 km on average [22]. The result is that 5,710,124.82 lt/year is consumed.

To calculate the amount of CO_2 emitted, we have the relationship that 1 litter of diesel generates 2.65 kg of CO_2 [25], so that for the 5,710,124.82 lt/year, 15,121,830.*76 kg* is generated of CO_2. Emissions of other pollutants such as nitrogen oxides (NO_X), carbon monoxide (CO), sulfuric dioxide (SO_2) and particulate matter would also be reduced.

A negative impact of using the proposed technology corresponds to water requirement for H_2 production, but Cuenca has an advantageous position because of the water availability that then is recovered when combusting the H_2 fuel. To produce 1 kg of hydrogen requires around 10-12 litters of water [26]. If 11 lt/kg of H_2 is taken as a reference value, based on the demand for kg of hydrogen from the bus fleet, 3,261,065 kg/year, 35,871,715 lt/year of water is needed.

B Economic implications

For an economic analysis, the total power capability of the system will be considered, accordingly to the energy produced (212,974,794.51 kWh), applying the following equation:

$$P = \frac{E}{FP^{*} H} \qquad (12)$$

$$P = \frac{212.974.794,51 \text{ kWh}}{0,175 * 8760}$$

$$P = 138.926,81 \text{ kW}$$

Where:
E: Energy (kWh)
Q: Power (kW)
FP: System Plant Factor
H: hours of the year (8760 h)

For the plant factor of the system, it is considered between 15-20%, for calculation issues, an average value equal to 17.5% is used. The cost of implementing the photovoltaic system is \$1.69/W [27], multiplying potential by the estimated power (138,926,807.90 W), the total cost of implementation would be \$ 234,768,305, 35.

The production cost of H_2 is 1.77 \$/kg [19], considering the cost of electricity, water, supplies, electrifier, annual investment and operation and maintenance. Considering the demand for hydrogen from the bus fleet, 3,157,125.08 kg, the total implementation cost to produce hydrogen would be \$5,588,111.39.

Also, considering that each H_2 bus unit costs \$1,500,000, to replace 100% of the bus fleet (475 units), \$712,500,000 is needed. The initial investment is too high, which indicates possible disadvantages for the implementation of this system. But a slow initial introduction is possible since the installation of photovoltaics and the generation of H2 as well as the change of buses are scalable factors in time.

C Social Implications

Among the advantages of hydrogen vehicles, whether for direct use or through batteries, it can be said that [28]:

- Does not generate pollution, since they only generate water vapour.
- Refuelling time is short 3 to 5 minutes.
- Maintenance of hydrogen vehicles is minimal and simple.
- Hydrogen vehicles are silent and zero pollution.

Among the disadvantages of hydrogen vehicles, it can be said that [29]:

- The network of hydrogen service stations is insignificant.
- Currently there is not a wide variety of hydrogen vehicle models.
- Fuel cell vehicles, due to their components, such as hydrogen tanks, lead companies to develop only quite large models.

Public transport buses with hydrogen fuel cells are a great opportunity to implement Full Cell Electric Vehicle (FCEV) technology, since they are heavy vehicles that travel long distances daily and have a high operational demand.

4. Conclusion

Hydrogen is a fuel that can be produced on a scale necessary for use in all modes of transportation. In the future, H_2 will allow the full use of solar, wind, and hydropower, enabling the transition to a post-fossil age.

In the future, hydrogen will help reduce pollution through the application of fuel cells in vehicles, because its efficiency is 3 times higher that of gasoline engines, which can save costs in the long run.

Ecuador is a privileged country in terms of solar energy resources due to its geographical location. In the city of Cuenca, the average solar radiation is 1,528.51 kWh/m^2, which favours the exploitation of this resource thanks to its geographical location. To take advantage of the solar radiation of the city of Cuenca and produce electricity, the study was carried out in the Historic Center with the projection of installing solar panels on the roofs, and the surplus obtained from the panels was analysed, which reached 174.61 GWh.

In the city of Cuenca, public transport faces great challenges, such as the constant growth of the vehicle fleet, which causes traffic jams and environmental pollution. The transportation system consists of 475 buses that circulate in the city, emitting around 112 tons of CO_2 and burning 11,175 gallons of pollutant diesel per day. Regarding the environment, the use of H_2 is feasible since it does not generate greenhouse gases and does not affect environmental factors (atmosphere, water, soil and biotic component). This makes hydrogen a solution to avoid the depletion of conventional fuels and global environmental problems.

The next necessary stage is to analyze the situation of the urban power grid in an smart grid scenario, provoking in them the capability to conduct and manage surpluses to be taken to hydrogen generation plants.

5. Further Information

Questions concerning the preparation of papers may be addressed to the International Secretariat:

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