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Assessing the Feasibility of Hydrogen and Electric Buses for Urban Public Transportation using Rooftop Integrated Photovoltaic Energy in Cuenca Ecuador †

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Abstract: A main restriction of renewables from intermittent sources is the mismatch between energy resource availability and energy requirements, especially when extensive power plants are producing at their highest potential causing huge energy surpluses. In these cases, excess power must be stored or curtailed. One alternative is increasing urban solar potential which could be integrated to feed electric buses directly or alternatively through hydrogen (H_2) as an energy vector. H_2 from renewable electricity can be stored and used directly or through fuel cells. This study aims to determine the H_2 capability that could be achieved when integrating large-scale photovoltaic (PV) generation in urban areas. This analysis was carried out by determining the PV energy potentially generated by installing PV in Cuenca City downtown (Ecuador). Cuenca is in the process of adopting renewal of the public transport vehicle fleet, introducing a new model with an electric tram main network combined with "clean type buses". The conventional diesel urban transport could be replaced, establishing a required vehicle fleet of 475 buses spread over 29 routes, emitting 112 tons of CO2 and burning 11,175 gallons of diesel daily. Between the main findings, we concluded that the electricity that could be produced in the total roof area exceeds the actual demand in the study area by 5.5 times. Taking into account the energy surplus, it was determined that the available PV power will cover from 97% to 127% of the total demand necessary to mobilize the city bus fleet. The novelty of this work is the proposal of a combined methodology to find the potential to feed urban transport with urban solar power in cities, close to the equatorial line.

Keywords: renewable energies; hydrogen; energy vector; city integrated photovoltaics; hydrogen fuel cells; environment

1. Introduction

The efficient use of energy has become an increasingly important issue. The implementation of sustainable economy scenarios for clean energy supply, economic development, and the prevention of environmental pollution are mandatory [1]. Then, planning tools complemented with reliability are important to encourage decision-making for future policy adoption in the energy sector for the short and middle-term [2]. Therefore, it is intended to accurately assess the potential of different energy sources, providing guidelines for energy infrastructure projects to promote economic investment by the public and private sectors. In Cuenca, the potential of several different energy sources existing within the city borders had been previously determined. Eleven technologies that could be applicable in Cuenca city were determined, and five technologies were detected as the main alternatives, through a multi-criteria selection process: Solar PV and Solar Thermal, mini-hydro located through the urban causes of the four rivers within the city, the energy potential available on the urban waste deposits and the energy available on urban wastewater treatment plants [3]. Then, in continued research, the energy potential of these five alternatives was also determined, detecting that the main source of energy is solar radiation and the best alternative by far is solar PV which, on its own, could supply next to 10% of the total energy consumption in Cuenca. The main restriction for reaching a higher potential is not the irradiation availability but the greatest consumption that actually is supplied by different types of fossil fuels dominated by transportation requirements. To achieve a greater margin, it is necessary to convert the current demands from fuels to electrical technologies. The other four energy sources would cover marginal urban demands and except solar thermal technology, they also serve to solve electrical needs as well [4]. Consequently, the research that must continue is precisely determining clean-renewable energy possibilities to cover transport demands.

The energy supplied by a city's energy sources through renewables is related and strategic to feed all its needs, provoking additional benefits in local economy, poverty reduction, and energy independence to some extent. The high population density of cities provides an opportunity for projecting energy development, considering its economy of scale in order to apply efficient use of energy production, wastewater treatment, waste, or transport infrastructure [5]. Recent worldwide research has projected alternatives to large-scale urban energy self-supply provision and management, aimed at reducing the required imports for energy consumption to solve every city's requirements [6].

Since the beginning of the 21st century, several studies have been conducted to determine to what extent cities could cover their energy requirements using the sun. In 2004, Compagnon et al. [7] established a methodological process using Radiance software to determine the urban fabric capability on building surfaces depending on the city's geometrical configuration of buildings. This research determined that solar irradiation is a great energy source that could contribute significantly to meeting the energy requirements of cities.

Subsequent research also has detected regional and local energy requirements and solar potential of buildings [8,9], which led to the development of the solar city concept [8]. However, to complement the energy potential of photovoltaic (PV) or solar thermal systems integrated into built infrastructure, it is important to change combustion energy consumption to equipment fed by clean power self-produced. Additionally, the mismatch effect, which is the most important limitation to achieving maximum energy self-sufficiency, needs to be addressed. This will make it feasible to take advantage of the entire energy potential as exposed by [10,11]. Even though the main urban energy requirements are associated with building requirements for achieving internal thermal comfort in extreme climate conditions, this scenario is different for cities located in advantageous climate locations. This is the case of cities located close to the equator in middle altitude valleys, where the main urban energy requirement is traditionally transportation. Then, changing transportation technology demands to power demands makes it possible to leverage huge amounts of electricity availabile. Then, if large-scale PV technology is introduced as an alternative to achieve a self-supply scenario, at moments when there is considerable irradiation available higher than the building and urban power needs, storage alternatives should be addressed.

In Ecuador, transportation policies for low-income families have been a traditional issue, as a consequence of the fossil fuel subsidies which means high expenses for the state budget. However, the country's location close to the equator means an important potential for producing electricity throughout the year with minimum seasonal fluctuation using PV systems. Under this scenario, hydrogen (H_2) has the potential to act as a clean and potent fuel alternative for energizing heavy cargo vehicles and heavy transportation requirements. Previous research had determined regional and different countries' capability to produce green energy from its renewable clean alternatives, developing local guidelines toward cleaning its energy matrix. Panchenko et al. describe the H_2 potential for different countries, detecting that there are different potentials and feasibility by different energy sources associated with the context. Then, local analysis is required to implement energy self-supply scenarios [12].

The proposed research analyzes the alternative of replacing conventional public transport systems with electric buses scenario and, alternatively, by powering them with H_2 cells, converting building PV power exceeding to H_2 for both alternatives. The case of Cuenca city downtown is analyzed as a representative case of urban areas located in middle-altitude Andean valleys close to the equator. In this climate context, almost 60% of the total energy requirements correspond to urban transportation [4]. In consequence, the main objective is to determine how much energy can be obtained from PV systems installed on the roofs of buildings in the urban area considering the high and stable solar irradiation and the low energy requirements of buildings due to good and constant climate conditions, allowing considerable power surpluses [13]. The energy storage potential of hydrogen cells for vehicle charging is estimated with the production of hydrogen with exceeding power. The H_2 potential is compared with the current data on public transportation requirements in the city.

In [14], it is suggested that under the concept of a low-carbon economy scenario for Ecuador, the use of electrolytic hydrogen could be an option for energy storage. The study analyzes the storage of hydrogen for conversion back to electricity using fuel cells, serving as a backup system for renewables. In Ecuador, several studies that have assessed the production of hydrogen from different energy surpluses obtained from hydroelectricity, PV, wind, and biomass energy were performed. This indicates a hint of local interest in investigating the production possibilities of this energy vector [15–17].

The analysis of H_2 production in Ecuador is not a new proposal [15–17], nor are studies that evaluate the uses [18,19] and potential [20,21] of PV solar energy. The novelty of this work is that it quantifies power surpluses potential from PV exceedings incorporated in urban areas to convert hydrogen to replace urban fossil fuels requirements.

The possibility of obtaining green hydrogen from urban areas has also been evaluated. A new approach from the point of view of urban metabolism is proposed to reach self-sufficient cities in terms of energy. These results are strategic to be applied in every urban center to decide the best possibility in concordance with requirements and local energy sources. In this investigation, it was found that the green hydrogen obtained from PV systems installed in urban areas is taking place in investigations throughout Ecuador. First, the methodology for measuring the overall solar potential in concordance with roof availability in Cuenca downtown is described. The power output capability was estimated according to the irradiation availability. The excess power is measured after supplying the entire urban power requirements. Afterwards, the H_2 conversion potential is calculated using the H_2 that could be obtained. Finally, the energy output feasibility to feed full-cell buses taking into account the energy requirements for actual urban transportation scenarios is calculated.

It can also be assumed that, if it is used in the entire urban area, the energy matrix of transport could be modified to make it more sustainable. In addition, it was concluded that for the production of hydrogen, it is possible to use renewable and non-renewable energy, since green hydrogen requires electricity and renewable water, thus avoiding environmental contamination. Figure 1 shows a schematic methodological process the calculate the possible power and H_2 production and uses of green hydrogen for transportation and the necessary infrastructure until it reaches the site of consumption.

The rest of the article is structured as follows: Section 2 describes the materials and methods, detailing the mathematical models, data, and information obtained in the background research. Section 3 details the results which are the analysis of the final uses of hydrogen in transportation, through the analysis of three case studies. Section 4 shows the discussion of the data obtained, with which a comparison is made with other investigations, and the environmental, social, and economic implications are also analyzed. Section 5 describes the main conclusions.

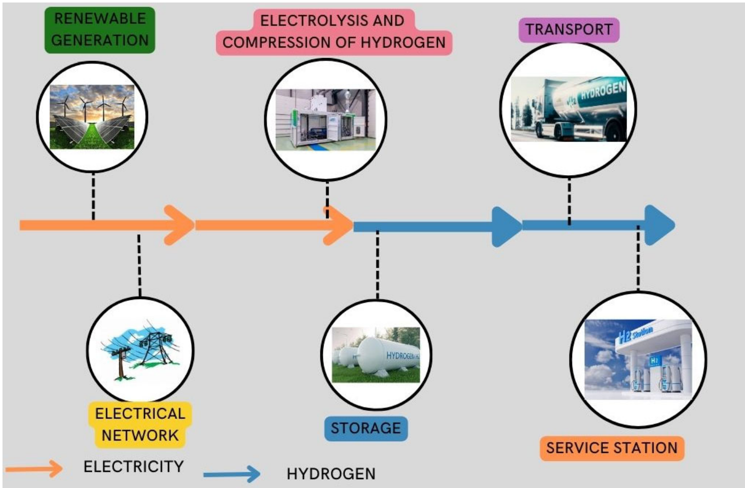

Figure 1. Green hydrogen production process.

2. Materials and Methods

The research site is delimited with the geographic information obtained from previous research performed by Urgilés and Yanez. They proposed a methodological process for determining the potential of urban pruning residues with municipal available data [22]. The radiation availability and possible energy output are estimated through the application of reduction indexes considering the local expected PV efficiency of the technology [23]. In this reduction index, architectural and geometrical restrictions, roof slope or roof orientation parameters, and technical reduction for inverters or electrical infrastructure were considered as well. Once this power potential is defined, the possible production of H_2 by electrolysis is analyzed, after feeding the current in-site urban requirements. Finally, we determined whether the H_2 produced could be used to replace public transport vehicles. Figure 2 shows the proposed methodological sequence.

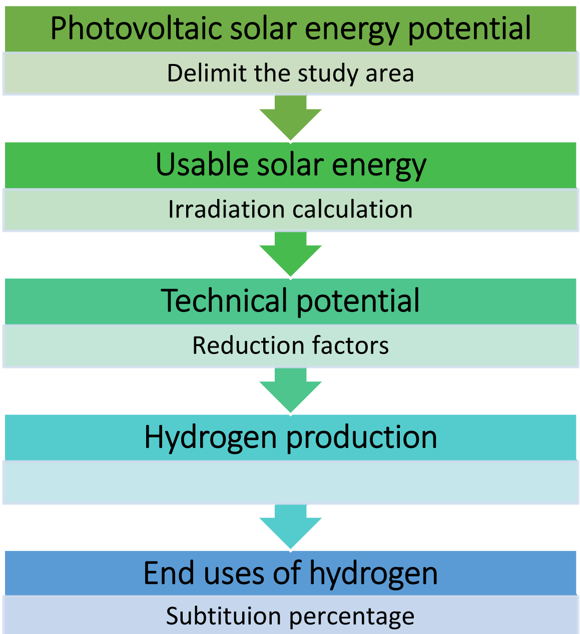

Figure 2. Proposed methodology.

2.1. PV Solar Energy Potential in Urban Downtown Cuenca

A central urban area is selected to define the roof PV power potential. This urban sector is mainly occupied by detached two-floor buildings, with inclined roofs, and mixed-use characteristics such as dwellings, commerce, service offices, and tourism services. The geographical data collected by Urgilés et al. [22] is used to delimit the research area, for which the INEC (National Institute of Statistics and Census) divides the City of Cuenca into 80 census zones. Figure 3 shows Cuenca City's location in Ecuador and South America and, additionally, exposes the solar irradiation availability in Cuenca city [23,24]. The expected power PV output is between 1400 and 1500 kWh by kWp PV installed per year. Even though the location has a medium potential compared to regions with very high solar irradiation, due to its closeness to the equator, the irradiation availability is very stable throughout the year. The urban morphology and building shape causes each roof façade to have a different orientation, and the roof slope that prevails accordingly with traditional architectural shape locally corresponds to a 33% tilt. As a consequence of the close distance to the equator, it has been observed in previous research that in any orientation of a roof façade, when the surface is at a low tilt, there is a high irradiation incidence, and the losses expected as a consequence of the orientation are pretty low [25]. In this study, the research area has been delimited to the downtown area of the city. This area comprises about 2.58 km^2, corresponding to 10 already registered census zones that have actual power requirements for buildings and urban needs.

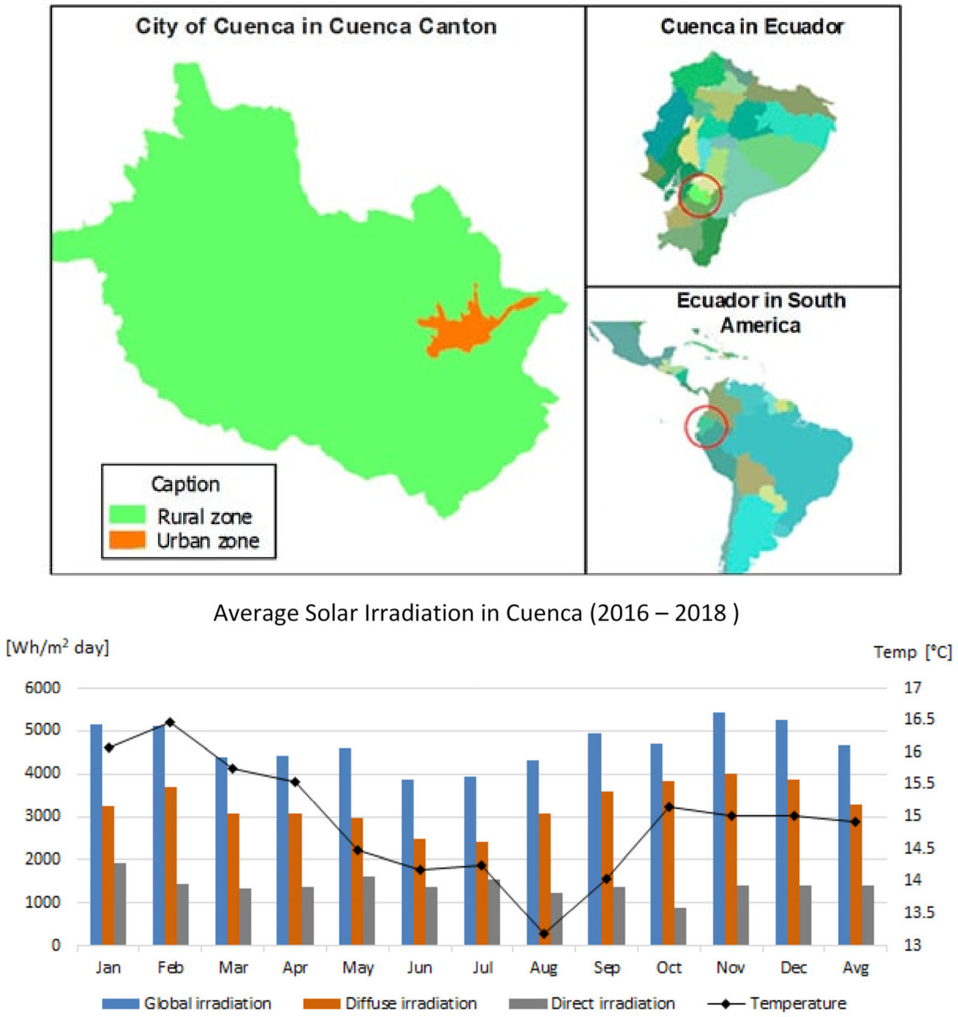

Figure 3. Location of the study area and PV potential [23,24].

The methodological process to estimate the available roof surface proposed by Urgilés et al. [22] corresponds to taking a sample of 20% of the buildings existing in each census zone, which it corresponds to 0.288 km^2. The following equation is then used to extrapolate the sample to the entire census zone:

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

Then, an roof area of 1.55 km^2 has been estimated. This corresponds to the total roof area of all dwellings in the 10 census zones that were selected for the study.

2.2. Estimation of Usable Solar Energy

Once the roof's exposure to irradiation has been determined, the urban solar potential of the Cuenca area can be assessed. In this study, the roof's exposure to irradiation is examined at a latitude near the equator. Theoretical considerations suggest that in the southern hemisphere, irradiation is maximized when the PV modules are oriented towards the north, with a slight inclination of the collector surface ranging between 3% and 4% for various orientations, and up to a 10% slope [23]. In concordance with the sun's high altitude at this latitude throughout the entire year and the direct sunlight incidence affected mainly by cloudiness, the best orientation for PV higher performance corresponds to PV facing to the east, nonetheless, the expected losses as a consequence of PV orientation are quite low with a 7% maximum reduction expected when comparing the best orientation with the worst one [23,24,26]. Then, all roof surfaces are capable of incorporating PV with minimal shadowing affection.

2.3. Technical Potential

The annual solar energy potential can be calculated using the equation [23]:

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

where P is the technical energy potential in kWh/year. A_{FV} corresponds to the area available for installation on the roof surfaces in m^2. I is the mean global irradiance in kWh/m^2 per year. Fr is the correction for architectural limitations and geometrical availability. n_r is the PV conversion in concordance with technological efficiency.

The local average annual irradiation considered is 1528.51 kWh/m^2 in concordance with [4]. Reduction factors (Fr) correspond to restrictions on the location of PV power based on architectural space availability and solar availability. In addition, the reduction factors (n_r) have also been included like the PV efficiency considering inverters, climatic and environmental conditions, dirt and shadowing effect, considered as the main characteristics affecting the irradiation incidence, the temperature of the cells, and other aspects that imply an efficiency reduction. The following equation is used to calculate Fr [23]:

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

where C_{con} represents the construction constraints. C_{prot} represents the limitations of historical buildings. C_{so} represents the constraints due to shadows. C_{or} represents the restrictions due to orientation. C_{in} represents the restrictions due to the inclination. C_{SM} represents the free space for the PV separation and maintenance routes on terraces. C_{FV} represents the availability for PV positioning. C_{ST} represents the availability for the positioning of solar collectors.

This equation results in a 0.62 value, according to values detailed in Table 1.

For the estimating of the solar potential reduction factor, PR was considered, which is the performance factor of the facilities, considering losses, wiring, orientation, inclination, etc. Giving a PR = 0.76, which is multiplied by the PV efficiency, 19% for monocrystalline modules ($n_{ef} = 0.19$), giving $n_r = 0.14$ in order to calculate the technical potential of the study area.

$$n_r = n_r * PR$$

$$n_r = 0.14$$

Table 1. The incident factors are taking into account for calculating the available roof area.

Reduction Factors	Value	Source
C_{con}	0.9	[27]
C_{prot}	1	[28]
C_{so}	0.8	[29]
C_{or}	0.96	[30]
C_{in}	0.9	[30]
C_{SM}	1	[9,31]
C_{FV}	1	[32]
C_{ST}	1	
F_R	0.62	Equation (3)

The energy potential of the PV technology in the complete urban area is:

$$P = A_{FV} * I * Fr * n_r \quad (4)$$

$$P = 212.97 \text{ GWh}$$

In 2020, the electrical energy consumption in the same urban area of Cuenca was 38,366.7 MWh; data were provided by the utility CENTROSUR [33]. In consequence, surplus EPVs are calculated using the following equation:

$$E_{PV} = P - \text{Total energy consumption} \quad (5)$$

$$E_{PV} = 174.61 \text{ GWh}$$

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

2.4. Production of H_2 from PV Exceeding

With the power exceeding the estimated value, it is possible to produce H_2 using a typical electrolysis process with high efficiency. Table 2 presents the specifications of a PEM electrolyzer, which boasts a 75% efficiency, and a higher calorific value of hydrogen at 141.86 MJ/kg (equivalent to 39.40 kWh/kg). This includes the necessary gas intake and purification systems, control systems, and auxiliary equipment [17].

Table 2. PV Hydrogen Production.

PV Hydrogen Production		
E_{PV}	174.61	GWh
n_e	0.75	
F_D	0.95	
HHV Sup	39.40	kWh/kg
P H_2	3,157,125.08	kg

Finally, in concordance with the electrolysis conversion system, FD of 0.95 as a conversion factor has been assumed [34]. Then, the mathematical expression to determine the amount of H_2 that could be obtained from solar PV power surpluses is as follows:

$$P_{H2} = \frac{E_{PV} * n_e * F_D}{HHV} \tag{6}$$

$$P_{H2} = 3,158,125.08 \text{ kg } H_2/\text{year}$$

The H_2 amount that could be potentially reached during a year with power exceeding's would be 3158.12 H_2 Tn.

2.5. Hydrogen Buses

Large vehicles powered by H_2 fuel cells have been considered to have better performance than those powered by direct hydrogen injection. This is because fuel cells are more efficient than direct hydrogen storage, and because large vehicles are constantly moving, which helps to offset the energy lost when hydrogen is stored in a liquid state. Also, large amounts of hydrogen could be stored, which is a positive aspect due to the low density of H_2. It is estimated that the consumption of buses is 10 kg H_2/100 km [34].

In order to carry out the analysis of the energy consumption of public transport in Cuenca, the typical average travel distance by the current diesel buses had been considered, and it has been estimated close to 68,654 km/year (188.09 km/day) in accordance with recent research data [35]. Cuenca's public transport system requires 475 buses distributed in 23 lines. The average length of the lines is 33.33 km and the average distance between stops is 309 m [36]. Diesel replacement of internal combustion engine buses by H_2-based buses was proposed. The vehicle fleet travels around 32,610,650 km/year, knowing the performance of H_2 buses, 0.1 kg/km, then 3,261,065 kg H_2/year is necessary. Comparing the diesel and route distances determined, we established that the amount of H_2 availability had the potential to cover 97% of the fuel demand required by the vehicle fleet to travel the current annual route.

2.6. Fuel Cells

Vehicle manufacturing companies develop research on storage alternatives (Table 3), gas service stations, or different options of storage using H_2 fuel cells. These are identified as having "zero emission", emitting only water vapor and a significant reduction in noise pollution. PEM-type fuel cells have the following characteristics:

Table 3. Characteristics PEM batteries.

Battery Type	PEM	Fuente
Range temperature	50–90 °C	[37]
Electrolyte	Membrane polymeric	[37]
Electrolyte status	Solid, which reduces corrosion and electrolyte management problems	[38]
Power	100 W–10 MW	[37]
Fuel	H_2	[38]
Oxidizing	O_2	[38]
Catalyst	Platinum	[38]
Efficiency	37–40%Average 38.5%	[38]
Investment cost	3000–4000 USD/kWh	[37]
Cell voltage	7–11 V	[39]
Application	Vehicles Space transportation	[37]

The energy value of H_2 has been measured at 39.44 kWh/kg [40], and the chemical conversion efficiency ranges from 37% to 40% of the maximum nominal power. For our calculations, we will consider an average efficiency of 38.5% [41]. Therefore, the useful energy obtained from the available hydrogen can be calculated as follows:

$$\text{Total energy}_{\text{PEM}} = \text{P}_{\text{H}_2} * \text{E}_{\text{H}_2-\text{SPEC}} \tag{7}$$

$$\text{Total energy}_{\text{PEM}} = 12,4517.01 \frac{\text{MWh}}{\text{year}}$$

Then, the electrical energy available with fuel cells would be:

$$\text{Available electric power} = \text{Total energy}_{\text{PEM}} * \text{n}_{\text{fc}} \tag{8}$$

$$\text{Available electric power} = 47,939.05\text{MWh}$$

Considering that the amount of energy required to mobilize an electric bus has been estimated to be 0.81 km/kWh [4] to 0.93 km/kWh [42], then, as before an average performance of 0.865 km/kWh has been considered. So, the possible distance to be travelled by electric bus can be estimated with the available power surpluses:

$$\text{Distance} = \text{available electric power} * \text{performance bus} \tag{9}$$

$$\text{Distance} = 38,830,630.55\text{km}$$

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

2.7. Direct Use of Electricity

From the excesses generated on the roofs of the Historic Center of Cuenca it is possible to obtain around 174,608,095.04 kWh (174.61 GWh) and knowing that the performance of electric buses is 0.865 km/kWh [4,42], the total distance of energy available can be estimated:

$$\text{Distance} = \text{available PV power} * \text{performance bus} \tag{10}$$

$$\text{Distance} = 151,036,002.21\text{km}$$

Considering the total distance covered by the actual bus fleet as 32,610,650 km, then, the entire bus routes could be covered 4.63 times.

3. Results

3.1. End Use for H_2 for Bus Transportation

The transport sector is by far the top urban energy requirement in Cuenca, with close to 60% of the total urban energy requirements. If the objective is to significantly reduce fuel consumption, urban pollution, and energy importations, then transitioning the urban transportation system from fossil fuels to alternative clean energy systems [32], such as H_2, becomes an obvious choice. Figure 4 illustrates the PV potential in Andean equatorial cities. It highlights the potential for supplying electric buses and compares it with H_2 combustion engines, H_2 cell engines, and electric bus alternatives in a comparative manner.

3.2. Hydrogen Buses

To carry out the analysis of the energy consumption of public transport in the city of Cuenca, the average distance travelled by a diesel bus has been considered, this distance is around 68,654 km/year (188.09 km/day) [32]. The total vehicle fleet then travels around 32,610,650 km/year. Accordingly with normal efficiency known with the current performance of H_2 energized buses of 0.1 H_2 kg/km [34], then 3,261,065 kg of H_2 is required per year. This analysis establishes that the available amount of H_2 covers 97% of the demand required by a fleet of vehicles utilizing H_2 to cover the same annual route.

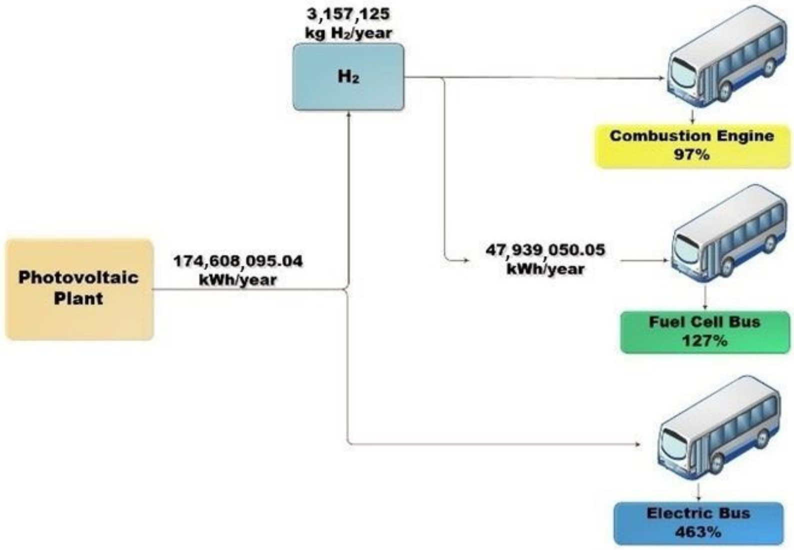

Figure 4. Use of hydrogen in transport.

3.3. Fuel Cells

In the analysis of the final use of H_2, the proposal is to replace the diesel currently used in internal combustion buses with H_2-based buses powered by fuel cells. The capability of H_2 to serve as fuel for these buses is derived from the power surpluses generated by PV installations on the rooftops of buildings in downtown Cuenca, as explained previously. Given that the vehicle fleet travels approximately 32,610,650 km per year, the available energy could cover 127% of the total distance travelled by this vehicle fleet.

3.4. Direct Use of Power on Electric Buses

From the possible power surpluses generated on the roofs of the Cuenca downtown, around 174.61 GWh can be obtained, and considering that an electric buses performance would be close to 0.865 km/kWh [4,42], then the total distance of available energy can be estimated. Considering the total distance demanded of 32,610,650 km, it is possible to establish that 463% of the route of the urban vehicle fleet can be covered.

In Cuenca, the industrial and commercial sectors are the main consumers of electricity. In the transportation sector, fossil fuels, primarily gasoline for private transportation and diesel for public and freight transportation, account for 90% of the city's fuel requirements. On the other hand, hydrogen possesses a high calorific value but is not naturally present, requiring the analysis of production alternatives. Therefore, hydrogen is usually considered an energy carrier or vector. The H_2 production can utilize both renewable and non-renewable energy sources. Green H_2, produced using renewable electricity and water, offers an environmentally friendly alternative, minimizing pollution. Hydrogen may be produced on a scale sufficient for use in various modes of transportation. In the future, hydrogen's potential to reduce pollution will be driven by its application in fuel cells for vehicles, as they exhibit three times the efficiency of gasoline engines, resulting in long-term cost savings.

4. Discussion

The environmental analysis focuses on determining the amount of carbon dioxide emissions avoided by changing the technologies used in public transport. Ecuador ranks 97 out of 242 countries in terms of annual emissions per capita, with 2.5 tons of CO_2/person [43]. The transportation sector is the main contributor to Cuenca's greenhouse gas emissions. In 2014, the total CO_2 emissions within the city boundaries reached 1,372,434 tons/year, from this, 801,285.9 tons/year corresponding to 58.4% is a consequence of combustion in vehicles. The emissions from diesel urban buses represented 5.6% of emissions from the transport sector [43].

To assess the positive environmental impact of the use of H_2 in the entire bus fleet in the city of Kunming (China), the total consumption of diesel fuel was determined based on the annual distance travelled [43]. By extrapolating this parameter, a value of 0.175 L/kilometer was considered, allowing for the determination of the amount of CO_2 produced from the consumption of diesel fuel in Cuenca's buses, which travel an average of 32,610,650 km per year [4]. The result, when viewed as an annual consumption, corresponds to approximately 5,710,124.82 L of diesel. Using the correlation that 1 L of diesel produces 2.65 kg of CO_2 emissions [44], the total amount of diesel consumed generates 15,121,830.76 kg of CO_2 emissions. Additionally, the reduction in emissions of other pollutants, such as nitrogen oxides (NO_X), carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter, will also be achieved.

A negative impact of using the proposed technology corresponds to the amount of water required for H_2 production, Cuenca has an advantage in this regard, because it has a lot of water. This water is recovered when combusting the hydrogen fuel. To produce 1 kg of H_2 requires around 10–12 L of water [45]. If 11 L/kg of H_2 is taken as a reference value, based on the demand of a kg of H_2 from the bus fleet, 3,261,065 kg/year, or 35,871,715 L/year of water is needed.

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

$$P = \frac{E}{FP * H} \tag{11}$$

$$P = 138.93 MW$$

where E: Energy (kWh), Q: Power (kW), FP: System plant factor, H: hours of the year (8760 h).

The plant factor of the system, it is considered between 15 and 20% for calculation issues, an average value equal to 17.5% is used. The cost of implementing the PV system is \$ 1.69/W [46], then multiplying this potential by the estimated power (138.92 MW), the total cost of implementation would be \$234,768,305.35 USD.

The production cost in Ecuador of H_2 is 1.77 \$/kg [34], considering the average cost of electricity, water, supplies, electrifier, annual investment, and operation and maintenance. Then, in concordance with the H_2 demand on the bus fleet it has been determined that 3,157,125.08 kg is required, the total implementation cost to produce H_2 would be \$5,588,111.39 annually. Also, considering that each H_2 bus unit costs \$1500,000, to replace 100% of the bus fleet (475 units) \$712.5 million USD is needed. But a slow initial introduction is possible since the installation of PV and the generation of H_2 as well as the change of buses are scalable factors in time. Among the advantages of H_2 vehicles, whether for H_2 direct use or through fuel cells [47]:

- They do not generate pollution, since they only generate water vapor when combusting.
- Refueling time is short: 3 to 5 min.
- Maintenance of H_2 vehicles is minimal and cheaper compared to combustion ones.
- H_2 vehicles are silent and non-polluting.

Among the disadvantages of H_2 vehicles, it can be said that [48]:

- The network of H_2 service stations is under development.
- Currently, there is not a wide variety of H_2 vehicle models.
- Fuel cell vehicles, due to their components, such as H_2 tanks, lead companies to develop only quite large models.

Public transport buses with H_2 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. Compared to Electric Buses (EB), FCEV charging time could be compared to refuelling the combustion ones.

5. Conclusions

In the city of Cuenca, the public transportation system faces significant challenges, including the continuous growth of the vehicle fleet, resulting in traffic congestion and environmental pollution. The current transportation system consists of 475 buses, emitting approximately 112 tons of CO_2 and consuming 11,175 gallons of diesel per day. To harness the solar radiation available in Cuenca, a study was conducted in the central downtown area, demonstrating that by installing PV solar panels on rooftops, the energy requirements of buildings can be fully met. Additionally, the surplus energy generated would be sufficient to cover approximately 5.5 times the power needs, resulting in a potential annual surplus production of close to 174.61 GWh. Considering the energy surplus, we determined that the excess energy would cover 97% to 127% of the total demand required to power the city's bus fleet.

The use of hydrogen in transportation would eliminate polluting emissions, equivalent to 60% of the city's greenhouse gas emissions. Diesel and gasoline usage would gradually be phased out in favor of this more environmentally friendly fuel. However, it is important to address certain environmental concerns, such as the substantial water requirement associated with the hydrogen energy cycle, which should be further investigated in future research.

Hydrogen represents a viable alternative fuel that can be produced on a sufficient scale to meet the energy requirements of all modes of transportation. In the future, H_2 will enable the full utilization of solar, wind, and hydroelectric power, facilitating the transition to a post-fossil fuel era. Moreover, H_2 application in fuel cells for cars, with its three times greater efficiency compared to gasoline engines, has the potential for long-term cost savings while reducing pollution.

This work contributes by presenting a methodology that allows the comparison of different options to utilize power surpluses for clean transportation, thereby reducing emissions and relying on urban electrical microgeneration. The results described herein, combined with local technological development, can aid in making more informed decisions. However, successful implementation will require political support and decisions, along with public and private interest, particularly in the initial stages of technology adoption.

Furthermore, it is crucial to address storage limitations in future research. Despite hydrogen being a lightweight element, it occupies a considerable volume when stored. Thus, thorough research on this issue is necessary. Additionally, future research should focus on the practical implementation at a scale that allows for a comprehensive understanding of potential barriers and limitations when adopting clean hydrogen in real-world scenarios.

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