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Long-term planning for the integration of electric mobility with 100% renewable energy generation under various degrees of decentralization: Case study Cuenca, Ecuador

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ABSTRACT

Urban borders are expanding in cities, solar photovoltaic and wind energy are being used and decentralized more and more, while the electrification of transport systems is in permanent progress. Users trust more in the modernization of electrical systems giving rise to various applications. The efforts made by both the public and private sectors are isolated and are not framed within comprehensive planning. For this reason, cities must be fully planned and contemplated in their land use plans. This article presents a long-term roadmap for the comprehensive electrification of mobility. To achieve a proper approach, it is based on the EnergyPLAN tool that uses the concept of smart energy and determines the long-term scenarios, the case of study is for the City of Cuenca in Ecuador. It seeks to take advantage of the potential of renewable energies available in the territory, which are evaluated and provide the necessary energy to feed future decentralized transport systems with a view to 2050. The long-term results show that the energy mix would be composed of wind with 37.3%, followed by solar photovoltaic with 33.9% and hydroelectric with 25.4%. There are others technologies such as biomass that do not exceed 3.4%.

Keywords: Clean energy; Energy Planning; Smart energy; Power sources; Energy transition; Electric mobility.

Nomenclature

ARCONEL	*Electric Regulation and Control Agency*
CMSS	*Coordinating Ministry of Strategic Sectors*
GHG	*Greenhouse Gas*
IEA	*International Energy Agency*
IDB	*Inter-American Development Bank*
MEER	*Ministry of Electricity and Renewable Energy*
NEA	*National Energy Agenda*
NGO	*Non Governmental*
NZE	*Net Zero Emissions*
OLEE	Organic Law of Energy Efficiency
PE	*Primary energy*
PV	*Photovoltaic*
RE	*Renewable Energy*
TOP	*Territorial Ordering Plan*
UNDP	*United Nations Development Program*
WHS	*World Heritage Site*

1. Introduction

The decarbonization of transport represents one of the main challenges to meet the goals of reduction defined by the countries, through their nationally determined contributions in the context of the Paris Agreement [1]. The electrification of transport systems is presented as a forceful action to transform our mobility and at the same time, improve our quality of life [2]. Undoubtedly, the move to electric mobility is one of the biggest revolutions that are happening in many countries of the world, especially in the European Union [3]. Latin America is aligning itself to this purpose, however it must continue to strengthen its policies within their countries and cities to be part of this change transformer [4].

There are several broad cutting-edge issues that seek to become climate neutral at a general level which are considered to have a direct impact [5,6], among them is the issue regarding a low-carbon energy model, zero-emission transport, the increase in efficiency, the resilience of the territory and the natural environment, the promotion of innovation and the transfer of knowledge [7]. Climate change is one of the most urgent environmental challenges that all nations on the planet have to face [8–10]. According to the Ihobe portal [11], Over the past 150 years, the global temperature has risen by approximately 0.8ºC, and is projected to continue doing so. These changes in the climate are having direct consequences in sectors such as agriculture, forestry, energy production, tourism and infrastructure in general [12].

Urban development in Latin America, the high rate of motorization, the impact of transport emissions on public health and the global warming, they demand strong decisions to the states and territorial constituencies for a transformation of transport systems [13]. For these purposes, it is important to draw the roadmaps that allow investors, legislators, researchers and governments to make decisions [14].

As a majority of countries of the region venture into mobility electricity, technologies are put to the test, incentives are created basic, the first ones are installed charging infrastructures – typically slow load centers [15]. In reality, countries are moving at their own swing. Some lead the transition to mobility electricity, others proceed with caution. While that a smaller group of countries is still in a waiting phase and still relying on oil. The fastest growing countries have created national and local strategies that involve several public entities and, critically, to the sector private [16]. They have understood the vision of going beyond a ministry and the national government. where still there is a gap and in some cases the state bureaucracy has been avoided and solid strategies have been created to advance at a good pace, it is in the involvement of the users, which could come later. The greatest efforts are emerging not necessarily articulated by governments at the national level, but also in local governments [17]. Some municipalities with the support of the private sector, including the academic sector, have opted for faster and substantial than national governments, with a strong focus on electric buses and taxis.
It must be recognized that the region has favorable conditions for the electric mobility: in this sense, three large manufacturers of automobiles operate in the region (Argentina, Brazil and Mexico) [18] and three countries have large lithium reserves (Argentina, Bolivia and Chile) – critical material for vehicle batteries electrical [19]. In addition, the region has the largest world percentage of energy sources renewable [20]. Chile also has large copper reserves [21]. Therefore, beyond the importation of vehicles manufactured in other latitudes, there is an opportunity to industrialization in vehicle manufacturing electrical and material processing premiums for electric mobility, according to international best practices.

Organized society and, above all, those truly interested in electric mobility play a crucial role in the adoption of new technologies [22]. In the main cities there are electricity companies that have demonstrated their commitment by investing in various pilot projects and in installing vehicle charging infrastructure electricity is the case example of the City of Cuenca [23] where the Centrosur Regional Electric Company in conjunction with the local academy has undertaken an interesting task to install recharging points inside the city and a route to the coastal city of Guayaquil [24]. The private sector also already sees a good outlook for developing an industry attached to an energy transition in Ecuador [25], even from the academy updates are already being visualized in the academic curricula in order to be prepared for a technological change that will grow exponentially in a medium term in the city of Cuenca and throughout the country [26]. In this first phase, the market is still small electric vehicle fleet plug-ins in most countries are not enough, they are below 10,000 units [27], with the exception of Colombia and Mexico [28]. Most bus fleets electrical are in the demonstration stage and they are modest, with the exception of Chile. Although in Ecuador there is the Organic Law of Energy Efficiency (OLEE) that requires the change of the fleet of buses to electric from 2025 [29], in the market there is still uncertainty in the impact of these technologies in the environment and the destination of the investments go or not to be propitious. The looming question is what should be done to expand the market and make buses, taxis and electric vehicles are the "new normal"? Two large areas will be necessary as a minimum: incentives and collaborations [30]. In South America especially, the countries should strengthen programs to provide temporary incentives and help reduce the initial price of electric vehicles, whenever necessary [31]. This might require pass electric vehicle laws in some markets, as well as accelerating the deployment of the charging infrastructure. In addition, it takes address cultural resistance to change and particular to adopt new technologies in a sector that historically maintained the same technology throughout the twentieth century [32].

1.1. Previous work

Various studies have been presented worldwide and have shown that renewable energies are effective solutions to provide sufficient energy for applications such as electric mobility, in fact, to date, it has not been possible to identify others structures that may have an impact in the face of the increasing increase in the temperature on the planet [33]. In this sense, transportation systems have been extensively addressed by several researchers with the aim of creating systems that are much more friendly to the environment and allow cities to keep up with routine activities without interruption. The alternative that is best connected to provide energy is taking advantage of the potential of renewable energies, which for the most part is in the same study site. Wind and solar photovoltaic sources are the most exploited, in some territories a high production of electricity is achieved through solar panels and wind turbines, while in other places that their energy potentials are not even so high, the population is much more willing to embrace these technologies and they are actually being of great use.

Within the most important advances in the last five years regarding the transition with a view to electric mobility, various studies can be recognized. Among them is the one presented by Thu Hien Dao et al. [34] in which it is stated that one of the factors for technological development is emigration, which first increases and then decreases as a country experiences economic development. It was first hypothesized by the mobility transition theory, then it was possible to explain the ascending segment of the curve and decompose the main drivers towards the electric transition in mobility. G Marsden et al. [35] states that the factor that most affects is that of intelligent governance, which is capable of making investments in a planned manner with a transformative mentality that will change the usual way of thinking about what, how and who governs the mobility system. A Moradi and E Vagnoni [36] carried out a multilevel perspective analysis to identify patterns referring to the dynamics of the urban mobility system and from there they traced the paths of energy transition in mobility. J Richey and A Rosburg [37] state that the success of an energy transition lies in showing the citizen that with the new established order greater economic development can be achieved and above all that there is sufficient purchasing power in the citizen to achieve the desired success.

Under this perspective of aspects for and against regarding the transition in electric mobility, a large number of researchers and experts related to mobility propose long-term roadmaps with the framework of renewable energies as their main ally [38–41]. With this, it is possible to minimize aspects such as the lack of immediate investments and the resistance to current change of the inhabitants. In this sense, Heike Proff and Thomas Fojcik [42] propose Innovations of the business model in the automotive sector in times of long-term discontinuous technological change. The Mobility 2050 proposal arises, highlighted in great detail by the reference [43]. Along these same lines, renewable energies in transport 2050 are strongly linked to achieving a future of sustainable mobility with the use of zero-emission fuels. Various regions, countries and cities have already drawn up their long-term roadmaps with the purpose of promoting mobility with technologies that are much more friendly to the environment, and from now on they are already developing actions determined to improve their quality of life [44].

C. Thiel et al. in reference [45], the case of the European Union (EU) is presented, which modified the regulation regarding CO2 emissions from automobiles and analyzed the role of electric mobility in the long term to achieve the decarbonization of transport [46]. Some regions of Africa also pose roadmap for zero-carbon electrification of Africa by 2050 [47]. This research proposes to carry out the transition to green energy taking advantage of the renewable natural resources of the territory. In South America, roadmaps are beginning to be proposed for 2050, in the case of Bolivia a totally sustainable system is proposed that includes the energy, heat and transport sectors [48]. In this same aspect, in Colombia [49] the mobility scenarios in the main cities were proposed, according to the demographic and macroeconomic energy perspectives with a view to 2050. In the transition processes of the cities, there are the cases of Delhi [50] and Riga [51] that have innovative long-term plans towards 100% renewable energies that also include electric mobility, among their recommendations is a progressive increase in renewables and reduction of fossil fuels precautionary service all the time. I Batas-Bjelić et al. [52] presented a realistic vision of energy transition of Serbia based on lignite. In the United Kingdom and Sweden [53], a multilevel analysis of the transitions developed by sustainable mobility niches has already been carried out.

Liukai Yu et al. [54] addressed the case of China for the decarbonization in the transport sector as a Promethean responsibility. This study applied network evolutionary game theory to investigate the energy conservation and carbon reduction of the transportation industry in relation to the promotion of electrification. A. R. Babaie Pirouziana et al.[55] presented an Iranian case study for the integration of systems based on renewable energy for the transportation sector in 2050. In this study, the effect of merging the transportation sector with the transportation system was investigated. integration on energy production and total costs for 2050 in 5-year time steps. The results showed a significant effect in reducing the final cost from €41/MWh to €36/MWh which was attributed to the increase in generated power and the sharp drop in prices of power generation technologies as a result of this merger.

In addition to decentralization, the planning of the electrical system is being transformed with the introduction of new loads. Electric vehicles (EV), in particular, are currently being of interest to researchers for electrical system modeling due to their expected wide acceptance in the short term and the many network services they can provide [56].
Opportunities and challenges of large-scale EV adoption depend on your grid integration framework, there are several options: vehicle-to-home (V2H) charging through a home-related control system [57], vehicle-to-vehicle charging bidirectional with the local network according to the schedule of a local aggregator and vehicle to grid (V2G) that is charged bidirectionally with the electrical grid. V2G provides valuable grid services, especially higher system reliability and flexibility, reduction in frequency and voltage fluctuations, lower losses in distribution lines, and potentially lower operating costs [58]. V2G requires aggregator control technology and power lines that can support two-way transmission and communication of electricity [59]. Finally, V2G can help balance renewable energy and minimize the costs of charging electric vehicles [60].

Some energy models have been developed and refined from experiments and case studies. Recently, tools like Prospective Outlook on Long-Term Energy Systems (POLES), used to assess the energy impact over time [61]. There is a set of open source OSeMOSYS tools [62] and the TIMES-PLEXOS model to investigate the energy system [63], among its main developments is the Australia case; Hans-Kristian_Ringkjøb et al. [64] used TIMES to investigate European energy system; Stefan Jaehnert and Gerard L. Doorman [65] combined EMPS and IRIE to understand the energy balance between input and output power systems. On the other hand, accounting models such as LEAP provides a more transparent model that is flexible to take into account technological changes, economic cost and potential for GHG emissions reduction [66]. Gustavo Haydt et al. [67] also used LEAP, MARKAL/TIMES to investigate the Atlantic Ocean power system for the Flores Island (Azores). H. Lund [68,69] developed EnergyPLAN used for the Danish energy system and has had a special connotation when applied without barriers in various countries of the world for the design of intelligent energy systems [70].

Various investigations recommend that before committing financial resources to energy transition processes, it is important to design roadmaps [71–73]. No process has come out of nowhere without being designed and subsequently discussed, for this purpose different software is currently available and most are effective and recognized worldwide, in this case study EnergyPLAN is used as a highly recognized and above all very flexible when carrying out the simulations, among the most relevant and recent studies that use EnergyPLAN are several that focus on the concept of smart energy systems.

EnergyPLAN has been developed in line with the concept of smart energy systems as defined in various published articles [74–76]. The term Smart Energy Systems it was first introduced in 2012 [77]. also often within control engineering and management, it has been used as a synonym for Smart Grid which is not correct. The EnergyPLAN design emphasizes the option of considering the complete energy system as a whole as specified in the publication [70]. It is a fairly common case integrate RES-based variable energy into the electrical grid through the use of smart grids, which should not be considered as an isolated aspect, but as one of several means and challenges of addressing sustainable energy systems in general [78]. From the very beginnings, EnergyPLAN focused on the integration of CHP and RES in fossil fuel based systems with little industry integration, until some of the latest analyses, where EnergyPLAN integrates with other modeling tools to form even simulation environments. more complex. The goal is to address national energy systems or form modeling environments that include both optimization in the design module and simulation approaches.

O Bamisile et al [79] carried out a synthesis of sustainable and feasible decarbonization for 2030 and 2050 in the Chinese province of Sichuan, contemplated a systematic analysis of carbon neutrality through EnergyPLAN. Hongjun Zhang et al. [80] designed the transition line and the performance that storage technologies can achieve for Beijing in 2060 towards 100% renewable energy. The results highlight that solar photovoltaic energy will be essential in the mix of installed technologies with 92.7%. A. Sadri et al. [81] performed a procedure for long-term energy and environmental planning for the transport sector with limited data. The results show that S-PUB is the most favorable scheme for reducing environmental emissions and requires fewer resources. AM Elberry et al. [82] presented a case study from Finland on hydrogen storage for renewable energy integration in the power sector. The results showed a decrease of about 69% in CO_2 emissions and a decrease in fossil fuel-based energy accompanied by an increased ability to meet demand with fewer imports in both scenarios.

1.2. Motivation

This research presents the structure to integrate the electric mobility of the City of Cuenca in a 100% renewable way, motivated by contributing to a comprehensive, sustainable, decentralized and participatory management to leave behind the consumption of fossil fuels that are highly harmful to the environment, the heritage buildings and above all to the health of the people who inhabit this world heritage city. The city has started with some actions in favor of sustainable mobility such as the implementation of the 4 Rivers Tram, the creation of the cycle path network, among others. However, a roadmap is necessary to carry out the transition process towards electric mobility. To carry out an energy transition towards comprehensive electric mobility, it must be understood that the mobility components and the proper use of land must be friendly to the environment as shown in Fig 1. The use of the internal combustion engine in this study is not linked to the future of mobility under any point of view.

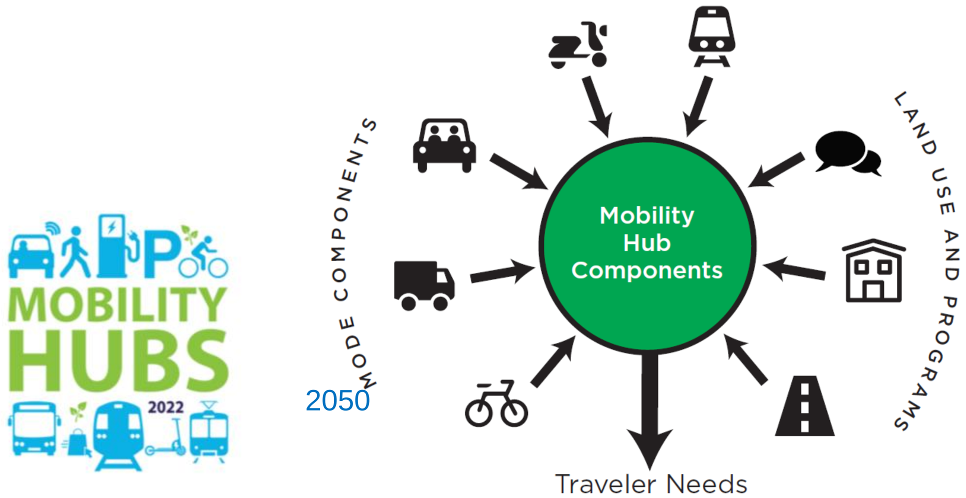


Fig. 1. Mobility hubs 2022 to increase their impact in 2050, without the presence of polluting components

The methodology has been organized as follows: In the first section, an analysis of the most relevant previous works related to the area of study and their motivations that led to carrying out this research are carried out. Then, section 2 presents the methodology used of the EnergyPLAN design tool to define the long-term electromobility roadmap in the city of Cuenca. Section 3 evaluates the current state of the city in terms of energy regarding mobility and the paths towards decarbonization by 2050. Section 4 analyzes the energy aspect and its transition process to leave fossil fuels behind, defining the base year and its projection, diversifying the potential sources of 100% renewable energy from the surrounding territory of the Cuenca canton that allows for an environmentally friendly transportation system. The results are presented and discussed in section 5 to finally issue the corresponding conclusions in section 6.

2. Methodology

In the current research, the roadmap that allows transforming the current mobility system with a low contribution of electricity systems and high use of fossil fuels is presented. The use of motorcycles and combustion engine vehicles are elements that have a negative impact due to their high pollution and noise in urban areas, which is why it is proposed that by 2050 they should disappear and be gradually replaced by ecologically friendly mobility systems. For this transition to take effect, the methodology considers, after its respective analysis, the availability of resources for the use of new technologies based on renewable energy sources and subsequently evaluates the impacts. In the methodological analysis, three analysis phases can be identified: The first is the data input phase of the available renewable energy resources and the data on fossil fuels used. The second phase of adjustment, based on state and local policies that allow a direct impact on the territory in analysis. Additionally, indirect aspects are considered, such as the more environmentally conscious generational change, technological development, reduction of production costs in new technologies both at the level of energy generation and consumption, which influences the easy access to new mobility. Finally, in the third phase, the technologies that are called to influence the future according to the demand for mobility are presented.

For this analysis it is essential to evaluate the current state (base year), made up of mobility systems based on fossil fuels and renewable energy. Current data on the levels of CO2 that is being emitted in the different parts of the city of Cuenca are entered and with this information it is established to correct this reality based on the inclusion of new environmentally friendly technologies at the generation level up to the demand for mobility itself, for this the concept of smart energy is used, which is being developed strongly from Europe and is giving interesting results worldwide as presented [70]. For the analysis and runs of information and to draw up long-term scenarios, specialized software EnergyPLAN is used, which has allowed a flexible and dynamic analysis of energy for long-term energy planning processes in different cities, countries and regions. For 2050, it is studied to achieve zero carbon energy in the city of Cuenca, it implies a systematic reduction of fossil fuels and, on the other hand, a greater penetration of renewable energy sources that positively affects the demand for electrical energy that will be growing by 2050 in the mobility sector.

2.1. EnergyPLAN analysis model

EnergyPLAN is a proven and highly reliable tool for long-term planning of energy systems and is not limited to certain territories and has rather spread globally as a design and forecasting tool. Among their applications, they have given rise to research that includes high percentages of renewable energies and in most studies zero carbon emissions are considered in the long term. The model was presented as version 6.0 in January 2004, since then much more widespread and more user-friendly features have been included, going through 15 versions until reaching version 16.2 currently available on its official site as of May 2022 (https ://www.energyplan.eu/training/documentation/). recently available and is shown in Fig. 2. The model allows feasibility studies, technical analysis, research for energy exchange between markets. In the end, as results, energy balances are obtained, details of the production components step by temporary step and in the end a complete renewable energy system. Subsequently, depending on the vision that the researcher has, extended and very particular analyzes of the sensitivity of a particular technology can be carried out and the economic benefits that can be achieved in defined time jumps can be evaluated.

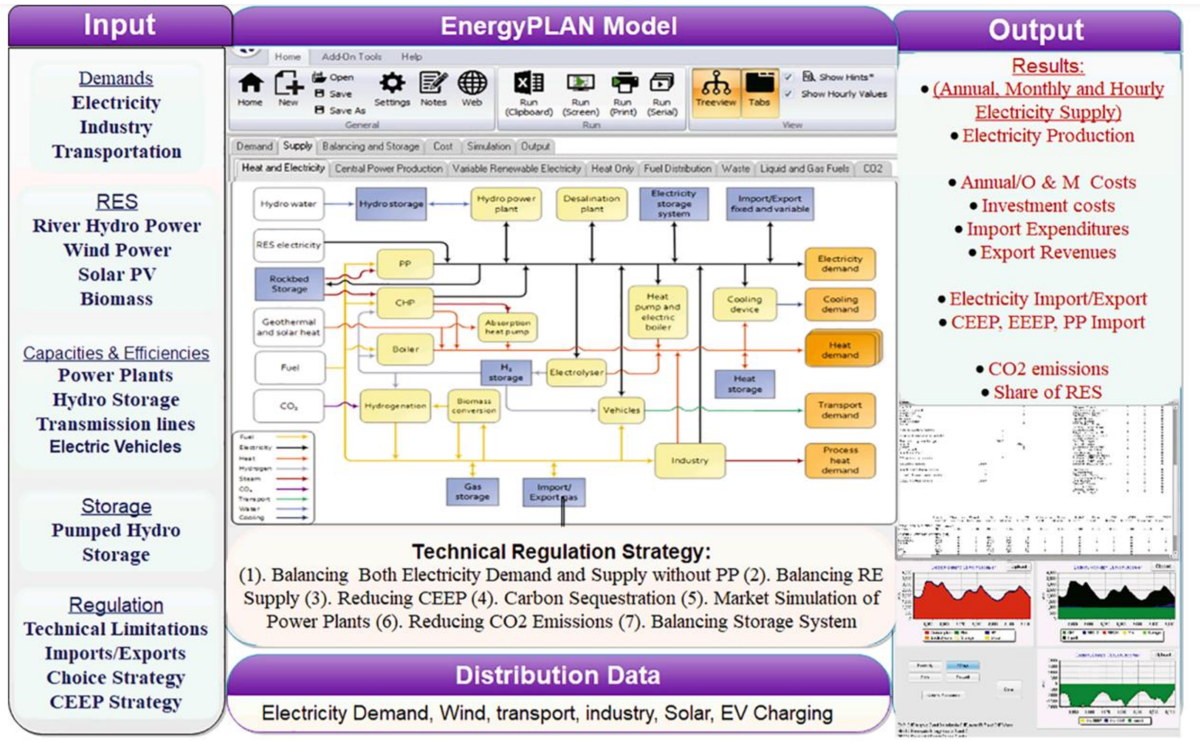


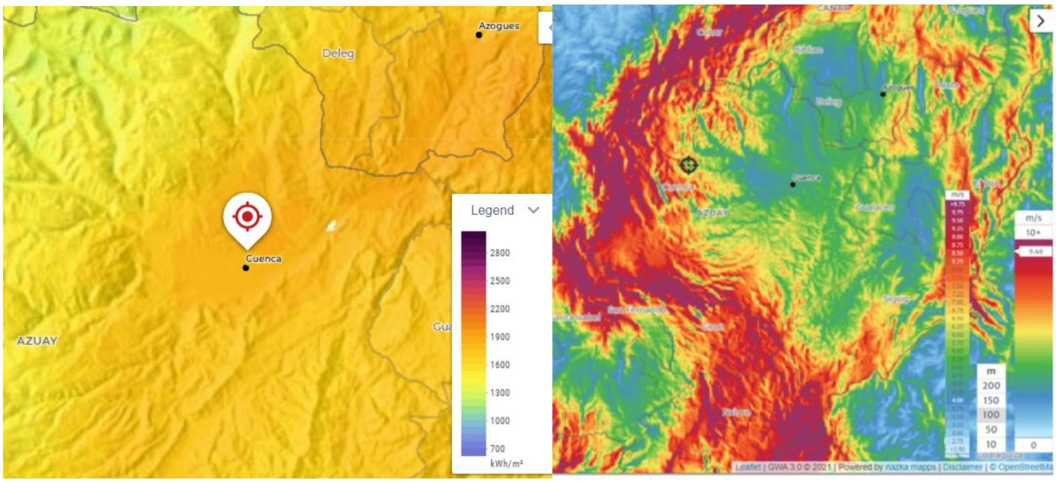
Fig. 2. EnergyPLAN model. Version 16.1 [69].

3. Situational analysis and the potential of renewable energies in the Cuenca Canton

Cuenca canton has become one of the main axes of economic development from Ecuador. The energy used for the development of the domestic, commercial and industrial sector comes mainly from conventional sources for the most part generation hydroelectric accompanied by generation using fossil fuels derived from petroleum such as gasoline, diesel, bunker and LPG. Population growth and the increase in energy demand has made it necessary to seek growth alternatives in the generation that covers this demand with hydroelectric systems that are part of current government policies and that have had a firm development in the last years.

Cuenca is located in the Inter-Andean Region of the Azuay Province. In the headwaters of this Province, large electricity generation projects have been developed due to its water wealth, especially in the area of the Paute River [83]. Although hydroelectricity has played a transcendental role in the energy matrix, this study proposes a diversified energy system from non-polluting sources, mainly wind and solar photovoltaic. The hydraulic energy in this study is maintained with the same current contributions and that will serve as the basis to carry out the proposal of a 100% friendly integral mobility with the environment. In the city of Cuenca there are quite interesting radiation parameters [84], which are in the order of 1800kWh/m^2, as can be seen in Fig. 3a.

Fig. 3b shows the Global Wind Atlas [85] cartography of the potential for wind power generation in the Cuenca Canton. In this case, when analyzing, it is observed that speeds greater than 7.87 m/s at a height of 150 m are found in the Rural Parishes near the city of Cuenca in the form of a fairly defined ring, which would allow the supply of wind energy towards the interior of the the city and that hybrid systems can very well be formed with other technologies such as solar photovoltaics. Wind speeds at a height of 100 m reach speeds of 6.8 m/s in these same parishes.



(a) (b)

Fig. 3. Renewable energy potential in rural areas referring to the City of Cuenca. (a) Solar irradiation. (b) Wind speed.

In relation to hydroelectric power, the Mazar and Molino plants are in operation, Sopladora is in construction process and Cardenillo has definitive studies for the bidding of the building. This hydroelectric complex is of vital importance for the country, generating only the power plant of Paute Molino 35% of the electrical energy demand of Ecuador [86]. The entire Complex generates more than 40% of the energy consumed in the country.

Paute Sopladora is the underground power plant of Sopladora, it is located on the right bank of the Paute River, between the Sopladora and Palmira ravines, crossing the river Paute through a tunnel with a subfluvial passage. It is designed to capture the turbined flows of up to 150 m^3/s directly from the two download tunnels of the Molino plant and lead them to the underground powerhouse through a tunnel 4.7 km long charge and a 338m pressure pipe. It will generate annually 2,700 GWh, through 3 units with Francis-type turbines [87,88].

The Paute Molino plant generates 4,900 GWh annually, for 35% of the country's electricity demand. It is composed of the dam Daniel Palacios, which is of the gravity arch type and has a height of 170 m, later, at 8 km in a straight line is the powerhouse in the cave that houses 10 units Pelton-type generators, designed for a flow of 200 m^3/s [89,90].

Paute Cardenillo in the final studies stage corresponds to the fourth and last stage of the comprehensive Paute Complex. Currently, it has studies and definitive designs for the tender for the construction of the project. Verdigris will be developed directly downstream of the Sopladora power plant, taking advantage of its turbined flow, plus that of the basin intermediate, taking advantage of 180 m^3/s. With an installed capacity of 593 MW, and it will generate 3,300 GWh per year. It will have a daily regulation dam, of the double curvature arch type of 136m high. It consists of six pelton-type turbines housed in an underground cavern located 4.4 km from the dam. It will have an additional generation unit of 7.3 MW at foot of dam [91]. The Mazar – Dudas project consists of 3 power plants hydroelectric plants, made up of two schemes, in the first the cascade plants called Alazán and San Antonio take advantage of the waters of the Mazar river, and the second corresponds to the Dudas plant that uses the waters of the Pindilig river [92].

3.1. Current state of mobility in the City of Cuenca.

The city of Cuenca is located at 2,538 meters above sea level and has a population of approximately 580,000 inhabitants. Its surface is 15,730 hectares and it has a climate with temperatures that oscillate between 14ºC and 18ºC [93]. The City of Cuenca faces challenges such as urban expansion, the increase in air pollution. Based on the analysis carried out by [94] in the city of Cuenca, Ecuador, 62% of the fossil fuels used in the city are used for transportation, while this sector is responsible for 58.4% of the total CO_2 emissions. Meanwhile, the industrial, residential and commercial sectors account for 43% of total energy consumption. Primary energy and consumption come from fossil fuels (gasoline 36.25%, diesel 29.05%, natural gas 14.81%, fuel oil 8.04% and GN 2.19%) and electricity 10%. In this same sense, it is detailed that conventional vehicles with Internal Combustion Engine (ICE) emit between 400 and 450 gCO2-eq/mile. This implies, if a vehicle has an average daily travel of 36 km/day, this could represent between 9 and 10.12 kg CO2/day. Just like many cities in the world face important challenges due to the exponential growth of conventional private cars, even in the city of Cuenca the use of motorcycles is alarming the population due to its levels of noise pollution, polluting gas emissions and the insecurity that this element entails.

According to the measurements of the Mobility Management Directorate of the Municipality of Cuenca, some 110,000 cars are registered in the city, but if the traffic from neighboring cantons and provinces is added, some 150,000 vehicles circulate daily [95]. In the city's official records of global sales of fossil fuels, a sale of 89,640,325 gallons of fuel is recorded, corresponding 52% to extra gasoline, 41% to premium diesel and 7% to super gasoline. In particular, Cuenca's public transportation is being operated by 475 buses in 30 bus lines that cover 113,000 km, emit 114 tons of CO_2 and burn 12,265 gallons of diesel every day on average [94,96,97]. It is imperative to generate policies that promote sustainable mobility. Some challenges outlined a priori are: the planning of the territory and land use in a much more appropriate way, the urban area must obey an exhaustive analysis to include elements of sustainable mobility and create the restrictions that merit in pursuit of the common good, control the disorder generated mainly by groups of foreigners in aspects of urban mobility, restricting the use of motorcycles and promoting shared transport or the massive use of bicycles through authorized places and cycle paths. Electric vehicles (EV) are called to promote the change towards the use of an efficient and environmentally friendly means of transport. Policies must be aimed at sustainable mobility that is inclusive but respectful mainly of citizens and achieve a peaceful, healthy coexistence in solidarity, especially with people with special abilities, where pedestrians are put above any mobility entity.

The 32% of the energy used comes from renewable sources, mainly from hydroelectric plants without considering that wind and solar photovoltaic technologies are practically unused and can be effective solutions for the transition processes in regards to electric mobility [98]. To reduce its emissions in accordance with its reduction goal, Cuenca has to increase the participation of renewable energies in its energy matrix and transform the transport sector making it electric, and it is here in this study where we provide the main lines to carry out with a view to 2050. It must also improve energy efficiency, particularly in the industrial and commercial sectors.

3.2. Executed actions that promote sustainable mobility

The City of Cuenca begins to develop in a sustainable way, thanks to the initiatives of its own people and the different authorities that are in the same line of work, unfortunately there is still a lack of a roadmap that allows transforming the current mobility system for a more environmentally friendly one. According to Fig 3, among the different mobility elements we have:

The Cuenca Tram has 27 stations. The length of the track is 20.4 kilometers (round trip), 1,435 millimeters wide in each direction and circulates at an average speed of between 22 and 25 kilometers per hour. The route from the first station to the last (10.7 km) takes about 35 minutes, while a car takes about 28 minutes. For the tram, 14 units are used (12 in service plus 2 in reserve), which run every six minutes during rush hour and the rest of the day every 10 minutes [99]. The studies calculate a minimum of 5,000 passengers a day and a maximum of 6,000 passengers, so according to the studies it expects about 4,000 daily passengers for a total of about 600,000 a year.

Cuenca reached 60 kilometers of infrastructure for the circulation of bicycles. This according to a report from the Mobility Company (EMOV EP), of the Municipality of Cuenca [100]. These are cycle paths, corridors painted on the road and some trails. The latter are mainly in the linear parks, next to the rivers, which are also spaces for practicing sports.
It is also important to highlight the BiciPública Cuenca shared bicycle system, which is made up of smart stations, distributed in different parts of the city [101]. The user can pick up the bike at the station through the application downloaded to his smartphone, returning it to any station after use. This system aims to offer the city of Cuenca a sustainable, healthy and non-polluting transport option. This is a project of the Municipality of Cuenca, operated by the company BiciCuenca. The Stations are powered by solar energy and connected to a central via wireless, which allows real-time monitoring of the bicycles and stations. The user can also follow this status and know exactly where he has stations / bicycles and / or vacancies available, through the Project's site or application.
Cuenca received a certification that distinguishes it as a "Bike Friendly" city. It is the first city in Latin America to achieve this qualification, which is awarded by a Spanish organization that works to promote bicycles [102].
At the beginning of 2018, the Cuencanos began to travel the streets of the city in the first 100% electric bus, in which citizens experience and learn about the qualities of this sustainable and ecological means of transport. These buses fit seamlessly into the topography of the city, giving rise to a new concept of urban mobility, traveling an average of 250 km per day [103]. They can be recharged without problems in one of the first charge stations (fast charger) that is located at the University of Cuenca.

The private company has invested in the installation of 4 fast charging electric stations for buses in Loja, Guayaquil, Quito and Cuenca, with a total charging capacity of 440kW. Performance tests of this type of vehicle are being carried out with private and public operators. There are various groups of investors that present to the Municipality of Cuenca several brands of 100% electric buses, increasingly innovative and with very good autonomy. The new electric units have a capacity to transport 86 passengers and a range of 300 kilometers [104]. On average, vehicles of this type need about four hours for a 100% recharge. These buses, by using electrical energy, do not pollute. They are equipped with top-level technology and have a digital central panel from which the entire vehicle is controlled.

Through an inter-institutional cooperation agreement between the Centrosur Regional Electric Company and the University of Cuenca, the first fast charging station for electric vehicles in Cuenca was launched, with an initial investment of more than USD 80,000 [105]. The fast charging station, inaugurated on April 12, 2022, has a capacity of 50 kW. This station allows charging up to three vehicles simultaneously through three different connectors. The charging time of the vehicle will depend on its autonomy; For example, for a vehicle with a 30% battery, it will take 12 to 20 minutes to reach a charge level of approximately 80%.

In order to promote electric mobility in Cuenca, focused on caring for the environment and the use of alternative means of transport, the Public Mobility, Transit and Transport Company, EMOV EP, tested 15 100% electric vehicles for eight days [106]. The electric vehicles purchased have a driving range of 403 km, a power of 120 kW, Lithium batteries and a maximum speed of 110 km/h. In the tests, the high-performance double-cab truck-type vehicle completed patrol work days, which had a daily duration of up to 16 hours of circulation. For this, slow charging was carried out for 7 to 8 hours a day to travel through different areas of the city, and whose test was carried out with the monitoring of energy consumption as performance in kilometers. An average charge of two hours at the 220-volt station gives the vehicle a range of 50 kilometers to travel around the city.

The Municipality of Cuenca is committed to regulating the circulation of: scooters, twikes, electric skateboards, segways, hoverboards, electric skates, longboards, electric unicycles and monowheels. These small vehicles, mostly single-person, whose presence in the streets and avenues of this city has increased significantly from 2020 but it must be recognized that they are friendly to the environment and deserve to be recognized as positive mobility elements. In some cases, they can exceed a speed of 70 kilometers per hour (km/h). Currently these roll freely through any space in the city, including parks, sidewalks, flower beds, green areas, squares, small squares and also through bike paths.

The municipality will provide the necessary means so that people can freely choose the way to move safely, through the establishment of public mobility policies. There is a regulation proposal in the cantonal Council of Cuenca that only contemplates vehicles of this type that do not exceed 25 km/h; whose weight is less than or equal to 100 kilograms (kg); and that they are human-powered or clean energy [107]. Also, that their size is less than or equal to an area of 1.30 x 1.95 x 2.70 meters (m), and that they have a load capacity less than or equal to 300 kg or one square meter (m^3). He calls them Personal Mobility Vehicles (PMV). Through this ordinance, it is sought that they travel in areas that present infrastructure that put their own safety and that of the rest at risk, such as tunnels, overpasses and exclusive lanes of the Cuenca Tram [108].

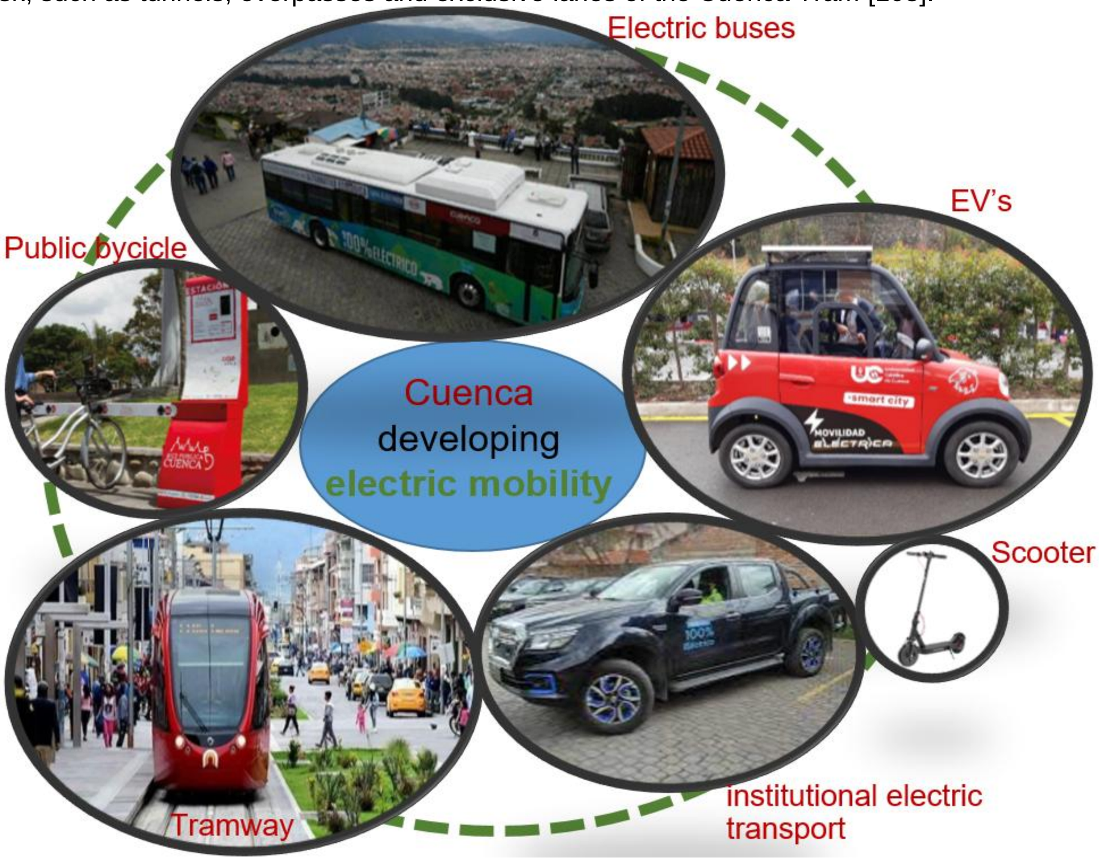


Fig. 4. Elements of electric mobility that begin to have a positive impact on the framework of public policies

4. Projections

Projecting 100% renewable systems, whether it be for a country, region or island, or as is the current case for a city, must face the challenge of integrating intermittent resources into the joint energy system and putting hour by hour electricity demand to safety, until the year 2050 covering 100% renewable energy from the Canton and its nearby places, thus freeing itself from fossil fuels. In the present study, the mission is aimed at achieving a 100% environmentally friendly comprehensive mobility system, this implies transforming all means of transport into electric ones, in the previous section it was analyzed that these systems are coupled to the reality of the Cuenca city. These conditions suggest that a nearby renewable electricity generation system is necessary, taking advantage of the generation potentials, especially wind and solar photovoltaic [109,110]. Considering the experiences of other cities worldwide and they do not necessarily have very high energy potentials but at the time they were very predisposed to accept these technologies, currently their mobility systems are a reality and they have an environment-friendly infrastructure, we have the cases from Lisbon [111], Beijing [112], California [113], Paris [114]. The dependence on oil in Ecuador on the one hand has been favorable but on the other it has been disastrous due to the high levels of contamination such as the breaks in the heavy crude oil pipeline due to earthworks [76,115], by the hand of man [116] and by transport of fuels to places of ecosystem fragility such as the Galapagos [117]. In addition to this, in Ecuador it has depended directly on a single source such as hydroelectric, although up to now it has been an effective solution, several researchers such as [118] and [119] warn that these decisions carry great risks in the long term and they advise taking immediate actions to diversify the energy matrix, they state that greater penetration of wind and solar power are viable options and in many countries and their cities they have become real solutions today.

The City of Cuenca has shown that it is possible to take advantage of energy resources such as solar and wind power, the academy has been the first to demonstrate, among them the Catholic University of Cuenca [120], where the sun's energy is used on the roofs of the Center Research and Technology Transfer, at the University of Cuenca in the new block of the Balzay Campus, its implementation is considered an investment of USD 1.2 million in its first stage, approximately [121], in the same way, a photovoltaic solar energy plant was installed at the Salesian Polytechnic University in Cuenca. It has an installed power of 12.6 kW, in 2019 16,790 kWh of electricity were generated [122]. Another of the important renewable energy facilities is located on the roof of the University of Azuay library, it has a peak power of 70kW and is made up of 192 360Wp modules of the latest generation monocrystalline silicon connected to a 50kW inverter [123]. In relation to the studies referring to wind energy, there are some among them in the Tarqui Parish [124], Molleturo [125], Quingeo [126] and they have generated expectations for their use but require significant investments for their deployment, which is why it is necessary for institutions of the State can take advantage of the wind resource for purposes of exploitation on a larger scale.
As the important advances within the Cuenca Canton have been noted and that the City can take better advantage of it but requires a roadmap for the energy transition in what corresponds to mobility. To carry out this study and propose the mobility roadmap, the EnergyPLAN tool is considered supportive to develop the proposal for 2050 in a 100% electric scenario.

4.2. Model of the energy system with a projection to 2050.

As expressed in the methodology, it is necessary to evaluate the energy system in the base year, have information on the available energy potential, the level of energy production and determine the Renewable Factor (RF) through (1) and (2):

$$Renewable\ Factor\ (RF) = \left(1 - \frac{\sum P_{non-renewable}}{\sum P_{renewable}}\right) x100 \tag{1}$$

$$RF = \left(1 - \frac{\sum P_{diesel} + \sum P_{gasoline} + \sum P_{coal} + \cdots \ldots \sum P_{others\ non-renewables}}{\sum P_{PV} + \sum P_{wind} + \sum P_{hydro} + \cdots \ldots \sum P_{other\ renewables}}\right) x100 \tag{2}$$

The sources that drive mobility in the city depend largely on fossil fuels, expressed with $\sum P_{diesel} + \sum P_{gasoline} + \cdots \ldots \sum P_{others\ non-renewables}$. Generalizing the model, it is necessary to evaluate all polluting sources. On the other hand, the renewable energy sources to intervene in the energy mix are the generation potentials available in the territory such as solar, wind, hydraulic, biomass, among others. $\sum P_{PV} + \sum P_{wind} + \sum P_{biomass} + \cdots \ldots \sum P_{other\ renewables}$. By 2050, this factor is expected to be mathematically $(RF = 1)$.

The base year serves as a reference for EnergyPLAN and after their respective runs, the time step value is introduced, in this case study it is for 2050, represented by (3):

$$TAPE = \sum P_{rene-2050} - \left(\sum P_{rene\ base\ year} - \sum P_{non-rene}\right) \quad (3)$$

TAPE(Total Additional Projected Energy) is a parameter that is determined based on $P_{rene-2050}$ considered as the Total Power to be supplied in 2050, $P_{rene\ base\ year}$ is the nominal power supplied in the base year, $P_{non-rene}$is the non-renewable energy used in the base year to be replaced by electricity from renewable energy sources.
Addicionally, the Energy Supply Ratio is determined as ESR, that evaluates the impact that renewable energies, when implemented in a territory, manage to satisfy the future demand for electrical energy for a time step from t1 to t2, as presented in equuation (4).

$$ESR = \sum_{t1}^{t2} \frac{P_{rene-2050} - P_{demand\_2050}}{P_{rene-2050}} \quad (4)$$

P_{demand_2050} is the projected electrical demand in 2050 and $P_{rene-2050}$ is the total renewable energy supplied in 2050.

If $P_{rene-2050}$> P_{demand_2050} There is a surplus of energy and it can be traded.

If $P_{rene-2050}$< P_{demand_2050} There is a shortage, it is an undesirable case and it would represent a serious drawback for electric mobility in the future.

If $P_{rene-2050}$= P_{demand_2050} It occurs when the production and consumption of electricity converge.

To avoid falling into the last two conditions previously exposed, this risk can be counteracted by implementing an energy storage system taking advantage of periods of time of excess energy production.

4.3. Reference electrical system 2022 and temporary step 2050

The energy system referring to the mobility of the City of Cuenca is made up of a large proportion of fossil fuels. However, it is noteworthy that in the base year it is evident that renewable energies are beginning to have a presence and their potential growth may have a notable shift towards electric mobility in the city. To carry out the projections with the support of EnergyPLAN, it is important to establish the base year (reference) and it is detailed in Table 1. The projection for 2050 implies that all the energy supply is 100% renewable, this is where wind and solar energy PV will play an important role in addition to the historical hydroelectric power. Contributions on a smaller scale will not be insignificant to diversify the energy mix and supply the demand for electricity from mobility systems.

It is important to indicate that in the base year 2022, over 98% of mobility is supplied by fuel. The available renewable energy is not yet being harnessed for the mobility sector. The transition process in this study focuses on providing the roadmap for the use of renewable energy with greater penetration of diversified renewable energies based on the available energy potential.

Table 1. Referential installed power of the mobility system in Cuenca.

Available renewable energy (MW)					Used fuels (MW)	
Hydro	**Wind**	**Solar PV**	**Biomass**	**Others**	**Gasoline**	**Diesel**
750	0.5	6	2	2	410	245

Table 2 below presents the general summary with the parameters used in the model.

Table 2. Validation of the reference model for the City of Cuenca (Electromobility).

Descriptive	**Solar PV**	**Wind**	**Biomass**	**Others**	**Oil**
Reference time (years)	50	50	50	50	28
Credit Capacity (%)	60	40	70	50	70
Order of merit	2	2	1	1	2
Fuel cost ($/TOE)	-	-	-	-	418.3
Maximum availability (%)	44	60	28	35	35

4.4. Results.

For the presentation of results, the technical and economic feasibility is analyzed in the respective modules of EnergyPLAN with a projection to 2050. In the base year 2022, an energy system in transportation directly dependent on fuels such as gasoline and diesel with 410MW and 245MW, respectively. The technological renewal that has currently been evaluated has been directly dependent on PV solar energy applications as detailed in subsection 3.2. These municipal initiatives allow the city of Cuenca to firmly promote being a sustainable city. The feasibility of satisfying the growing demand of 901,499 inhabitants in 2050 is marked according to data from [127]. Although one of the purposes is to replace fossil fuels and instead take advantage of electricity from renewable sources for electric mobility, it implies not drastically reducing polluting energies for social responsibility since there are jobs that must be protected. and raise a training plan to operate the new technologies with personnel from the same city if possible. As of 2030, hydroelectric energy is used in the same proportions as in 2040 and 2050, with the aim of diversifying the electrical system with both wind and solar PV as shown in Fig 8 when using EnergyPLAN. This criterion is in tune with what is recommended by María-Augusta Paim et al. in reference [128], in fact there are times of the year when the flows are quite low and border on 1.8 m/s in the area of the Paute River, being the regular between 4 and 6m /s for the hydroelectric production of Cuenca and the rest of the country. With regard to the outlined roadmap, none of the contributions of renewable energy have a downward trend. The technologies that are expected to have an impact in 2050 are solar photovoltaic with 400MW and wind with 440MW. The biomass with 15MW and others that could be included up to 25MW with a plan for the use of solid waste from the Cuenca Canton and its surroundings are also seen within the energy system for electric mobility, as shown in Fig 5 and Table 3.
The roadmap presented is considered realistically recommendable. There are resources such as solar radiation and wind that would lead to a greater use of energy, however a balance is sought between the different technologies. It is important to indicate that at the time of locating generation plants, installation in protected or patrimonial sites should be avoided in order to avoid subsequent social conflicts.

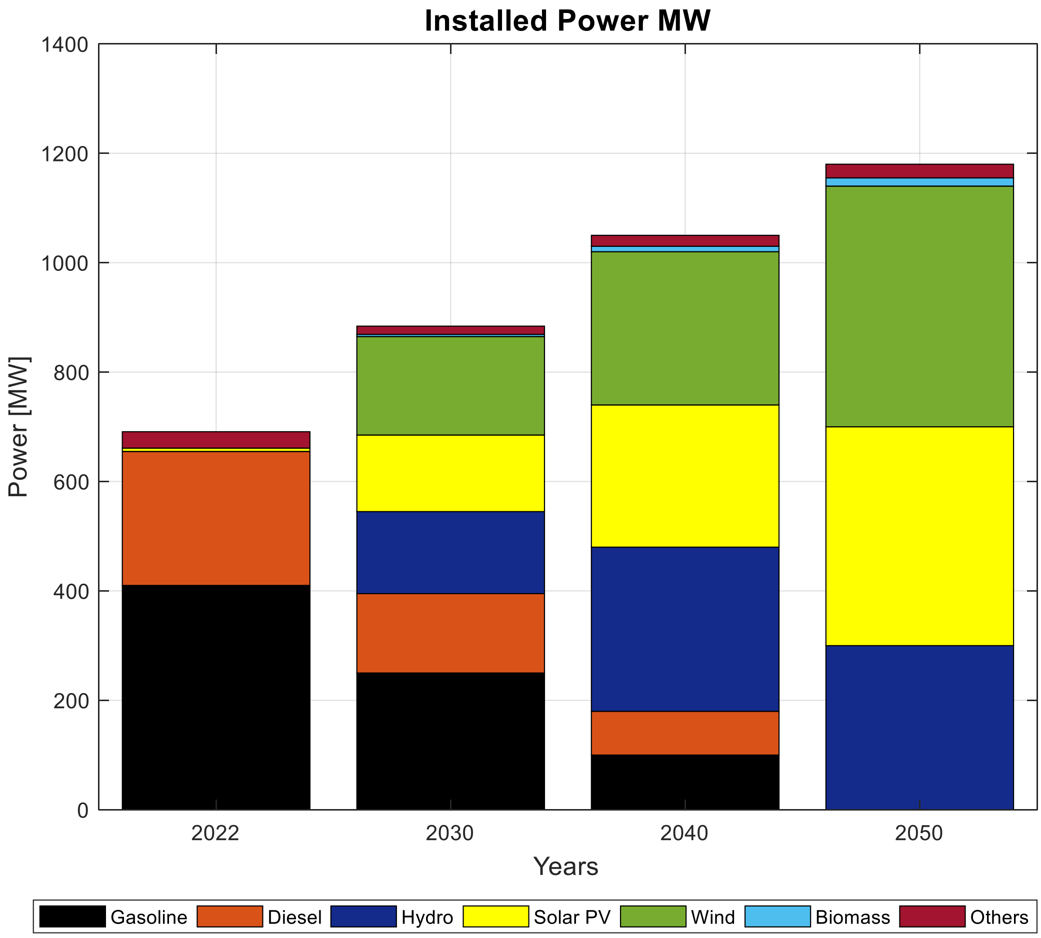


Fig. 5. Detailed installed power by source regarding mobility in the 2022-2050 scenario of Cuenca

Table 3. Results obtained from installed power 2022-2050

Source	2022	2030	2040	2050
Gasoline	410	250	100	0
Diesel	245	145	80	0
Hydroelectric	0	150	300	300
Solar PV	6	140	260	400
Wind	0	180	280	440
Biomass	0	4	10	15
Others	6	15	20	25

In Fig. 6 shows the complete energy mix for 2050, broken down by source.

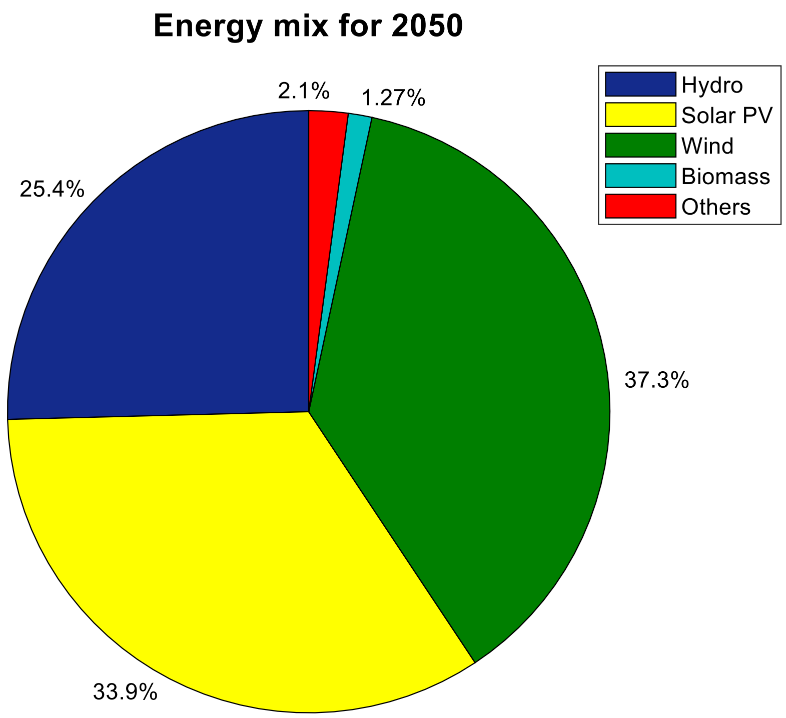


Fig. 6. Energy mix for 2050 capable of supplying electric mobility in Cuenca for 2050.

5. Discussion and analysis

Based on the results obtained, the technology that is called to be the energy support for the purposes of energy production is wind with 37.3%, followed by solar PV with 33.9% and hydroelectric with 25.4%. There are other technologies such as biomass that are a fairly low contribution with 1.2%. It is important to indicate that although hydroelectricity is currently essential to supply energy to the residential and industrial sectors, this technology is essential in addition to fossil fuels, but not in transport it would occupy the third position in importance but it will continue to be relevant for the decarbolization of transport in 2050.

Taking these initiatives at the country level and Cuenca has always been innovative in many daily aspects, implies that other cities would also take this energy transition model, given that by not having or at least limiting the points refueling companies will be forced to opt for these new mobility technologies. By expanding a network of charging stations, the facilities are expanded and users would make the decision to purchase an electric vehicle. If we talk about public transport right now, the Organic Law on Energy Efficiency is in force, in which article 14 regarding transport requires that from the year 2025 all vehicles that are incorporated into the urban public transport service and interparochial, in continental Ecuador, must be only electrically powered. Likewise, the decentralized autonomous governments are called to create the necessary ordinances to regulate these aspects of mobility that promote sustainable mobility, with sufficient economic resources to carry out this transformation in mobility seen from a global and marked point of view. in citizen welfare. In the same way, in the Plan for the Creation of Opportunities 2021-2025 of Ecuador, axis 4 of Ecological Transition that contains 3 objectives, 9 policies and 17 goals. Within the goal for 2025 is to increase the installed capacity of electricity generation from 821.44 MW to 1518.44 MW, which agrees that in the Cuenca Canton, having a fairly good renewable energy potential, it can facilitate the transformation of its energy matrix in the same direction as The central state would be doing it and possibly the economic resources that are allocated for these purposes can be better managed for the City of Cuenca.

The roadmap for 2050 in terms of mobility requires taking immediate actions to avoid relegating from a technological change that is coming with force and many countries are reorganizing their processes to implement transport structures that are much more friendly to the environment and Cities like Cuenca are called to be part of this change.

6. Conclusions and future work.

This research presents the current state of the transport system of the heritage city of Cuenca in Ecuador and outlines the roadmap for the energy transition of the transport sector to leave behind the use of fuels such as gasoline and diesel, taking advantage of the renewable energy benefits in strategic points of the Canton Cuenca and other nearby areas. This study is perfectly aligned with decree 59 for the ecological transition in which in its article 6 it is mandatory to develop and comply with priority public policies and public, private initiatives, public-private and community alliances that promote the transition towards production systems and sustainable consumption that lead Ecuador towards net zero emissions by the year 2050. In the literature presented, several authors who are addressing the transition processes applied to countries, cities or regions motivated to migrate their fuel-based mobility structures were highlighted fossil fuels to one that is friendly to the environment. The integral mobility system proposed in this study seeks to take advantage of the efforts made to date, promote them on a larger scale and progressively leave behind systems based on fossil fuels and have electric mobility systems.

The actions directed by the Municipality of Cuenca, the academy and the private sector have been giving good results and, above all, they have made it possible to identify possibilities for the use of renewable energy on a larger scale and would have a notable incidence in the temporary passage until the year 2050. The scenario that has been proposed for mobility in the City of Cuenca seeks to make it a development territory in Ecuador and a reference for other cities. The technical, meteorological, legal and ordering conditions for the use of urban land are favorable, which promote the implementation of environmentally friendly systems and transfer to fulfill this outlined purpose. Seen from the demand side, this energy transformation process must avoid suspensions of electricity services that affect mobility in the city and its territorial interrelationships. On the other hand, the transition process must contemplate a job reinsertion plan with their respective training, in which workers who close their jobs must be considered in the new jobs. The creation of decent employment is a responsibility of the central government and channels the actions through the Ministry of Labor in coordination with the local governments. It is not out of place to express the measures adopted in these energy transition processes must be socialized and maintain close channels of communication between their local government and the population to take the corresponding measures.

As future work, it is proposed to carry out an optimal analysis for the implementation of charging points for electric vehicles in a massive way in the city of Cuenca. In this type of research, current cartography and peripheral growth projections of the city available in the Municipality of Cuenca and other state entities can be used. Other investigations related to transportation can be of great contribution to establish optimal mobility nodes that facilitate the mass movement of people between sectors of the city based on their long-term urban growth.

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