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Methodology to Determine the Management of Demand in Recharging Electric Vehicles in Vertically Integrated Markets Includes Photovoltaic Solar Generation

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Abstract: The high penetration of photovoltaic solar generation and electric vehicles in developing countries and with vertically integrated electricity markets with restrictive regulatory policies enhance demand management and the participation of prosumers in optimizing their resources. In this sense, the research presents a demand management methodology based on the prosumer model for recharging electric vehicles through optimization based on linear programming to minimize recharging costs, considering the stochasticity of the solar radiation variables, vehicular mobility patterns, consumer preferences, and optimal location of charging stations through surveys and predictive tools such as PVsyst and GAMS, in such a way that the energy demand for recharging electric vehicles is met. This way, the methodology reduces power demand peaks and mitigates the economic and technical impact on distribution networks. This case study has been modelled with real information from electric vehicles, distribution networks, and surveys in Cuenca, Ecuador.

Keywords: demand management; electric vehicles; electricity market; optimization; photovoltaic solar energy

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1. Introduction

Traditional mobility systems based on fossil fuels are the most widely used means of transport today; it is estimated that in the next 50 years, oil reserves worldwide will run out. For this reason, the growing demand for means of transport and society, the responsibility to reduce greenhouse gas emissions motivates the increase in transport systems based on electricity [1,2].

The penetration of electric vehicles (EVs) worldwide has increased significantly in the last ten years; in 2011, approximately 110,000 EVs were registered as being in circulation, and in 2020, about 3 million units were incorporated; currently, they exceed 10 million units in circulation worldwide as shown in Figure 1, this represents an annual growth rate of 40% [3]. On the other hand, the market share at the end of 2020 was 4.2% in the global vehicle market; despite this significant growth in the number of EVs, these still represent a small fraction of the worldwide market for vehicles in circulation [4,5].

The massive introduction of EVs causes essential changes in the demand for electrical energy, problems in the network, and losses and a decrease in the quality of energy [6–8], which is why it is essential that studies focused on optimizing the demand for electrical energy are developed, promoting the use of non-conventional renewable generation for the self-sufficiency of said demand.

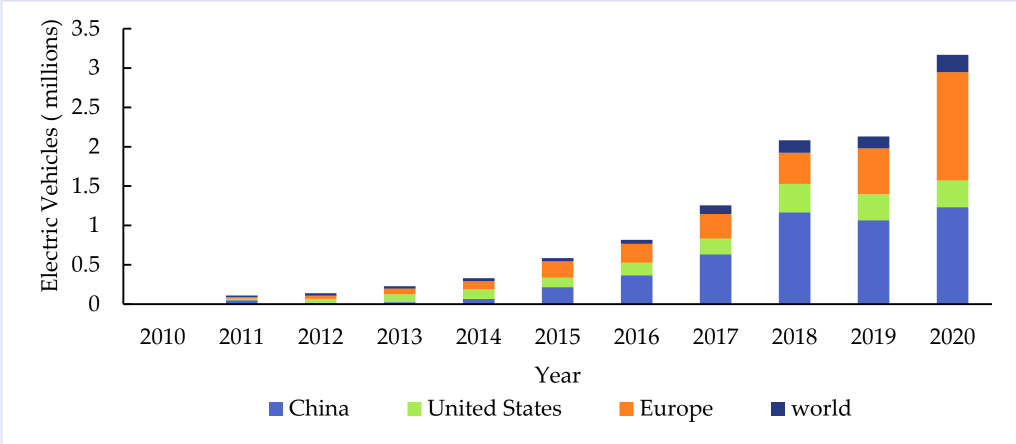

Figure 1. Worldwide sales of EVs in millions of units.

In this context, the research focuses its interest on the application of optimization algorithms through linear programming methods to manage the recharging of EV batteries, reduce costs, and meet the technical considerations required by the operator of the distribution system (ODS); through the "Prosumer" model, including an essential block of photovoltaic solar generation (PVG) [9,10] in its system.

At present, the PVG systems and the demand management in the recharging of EVs have a vital synergy. As cited by [8], the current studies on optimization and intelligent charging of EVs are reviewed based on the feeding of these loads through PVG, and in [11] it is shown that the regions close to the equator are the regions with the highest incidence of solar radiation, slight seasonal variation, and a constant pattern of radiation.

Studies such as [12] propose a two-layer optimization model to minimize operating costs, voltage variations, and energy losses in smart microgrids by implementing hybrid genetic algorithms, particle swarm optimization, and scanning algorithms.

In [13,14], it was proposed to reduce the negative impact produced in distribution networks due to EV recharging through demand management tools such as the aggregator, in which user preferences are considered in terms of time, power, and recharge mode.

For its part, [15] proposes charging strategies for EVs in isolated networks, modulating the charging power based on the wind and photovoltaic generation potential in the Galapagos Islands of Ecuador. A similar case is raised in [16] with the impact of long-term EV load management strategies on isolated microgrids. The study concludes that investing in PVG and an EV charging management strategy brings environmental and economic benefits.

In [17], the possibility of stochastic programming of EV aggregators to participate in the electricity markets and auxiliary services is studied.

In [18], the impact caused by the change from internal combustion vehicles (ICE) to EVs in Ecuador, such as Quito, Guayaquil, and Cuenca, is analyzed, raising the possibility of satisfying the demand for electrical energy through PVG through the theory of "urban metabolism", where a city can be self-sustaining with the resources of the generation.

In [19], the efficiency presented by the autonomy of electric vehicles in topologically irregular cities is determined; it presents the case study of Cuenca in Ecuador. To determine the efficiency, it uses variables of the city's mobility plan, measurements of real-time monitoring of EV battery discharge, altitude monitoring through GPS, electric vehicle control panel records, and surveys to estimate the use and level of penetration of this technology. From the analysis, he discovered that the efficiency is 67% and considered the electricity rate and regulatory aspects to determine the cost of charging the EVs. In addition, it simulates the penetration of EVs in the distribution network to infer consequences on the electricity demand profile that encourage the penetration of EVs.

The research presented here aims to ease and reduce the costs associated with this procedure with the following contributions.

- Analyzes the demand for electrical energy resulting from the recharging of connected EVs at fast charging stations through a case study with actual data to determine the technical and operating parameters that photovoltaic solar generation must meet to satisfy the demand for synchronism with the regulatory restrictions of Regulation 001-20 of the Agency for the Regulation and Control of the Ecuadorian electricity sector.
- Develops a methodology to optimize the demand for electrical energy from the recharging of EVs based on the self-supply capacity of photovoltaic solar generation through commercial transactions in a vertically integrated electricity market.
- Technical and financial analysis of the proposed methodology for demand management in EV recharging is carried out to determine the cost of energy and the economic indicators that contribute to the model's sustainability based on the potential of renewable generation.

This document is structured as follows: Section 2 presents the case study and analyzes the electricity market regulatory aspects and conditions to determine the technical and economic parameters used in the proposed methodology. In addition, EV penetration and behavior patterns based on citizen surveys are considered. In this case, stochastic variables are studied to determine the potential of photovoltaic solar generation. Section 3 provides an optimization algorithm for managing EV recharges based on the photovoltaic solar generation potential. Section 4 presents the results of the optimizing model and considers a financial evaluation of the methodology to determine the project viability. Finally, Section 5 presents the discussion and conclusions of the proposed method.

Table 1 summarizes the state of the art of the different methods used in demand management for charging electric vehicles using photovoltaic solar energy.

Table 1. Literature review of the methods used for the methodology.

Chapter	Theme	Subtopic	Reference
EV's recharge management methodology	EV as a contribution to sustainable electric mobility		[1–5]
	Effects of the introduction of EVs in distribution networks		[6–8]
	Potential for photovoltaic solar generation to recharge EVs		[9–11,18]
	Demand management models for EVs recharging		[12–17]
	Regulatory aspects in Ecuador	Technical aspects	[20]
		Economic Aspects	[21,22]
	EV's growth projection		[22–25]
	Generation parameters for the supply and recharge of EVs		[26–36]

2. Demand Management Methodology—Case Study Cuenca–Ecuador

The high penetration of electric mobility in developing countries presents accelerated changes in demand management and the participation of prosumers in optimizing their energy resources. Cuenca is located in the inter-Andean region of South America, specifically in Ecuador; it is a topologically irregular city (2000–3600 m above sea level). It is an intermediate city with around 700,000 inhabitants and presents important characteristics to provide its citizens with a good quality of life. It has good urban–rural connections, minimal environmental problems, quality electricity service, continuity, and 98% coverage.

The city of Cuenca uses 62% of fossil fuels for transportation and is responsible for 58.4% of total CO2 emissions, conventional vehicles with an internal combustion engine (ICE) emit between 400 and 450 g CO2-eq/mile; an average car travels a daily route of 36 km/day, which represents between 9 and 10 kg CO2/day [19].

The distribution of destinations reflects the relationships between the functional mobility zones, and these data are essential for the definition of policies that would be adopted with the inclusion of EVs, which is why the analysis shows the most significant modes of transport concerning the location of the destination of these trips in Figure 2. The total trips to the historic city center is equivalent to 38%; trips are mainly for work at 40%, followed by shopping at around 20%, and studies at 31% [19]. The predominant means of making trips is public transport, followed by private vehicles.

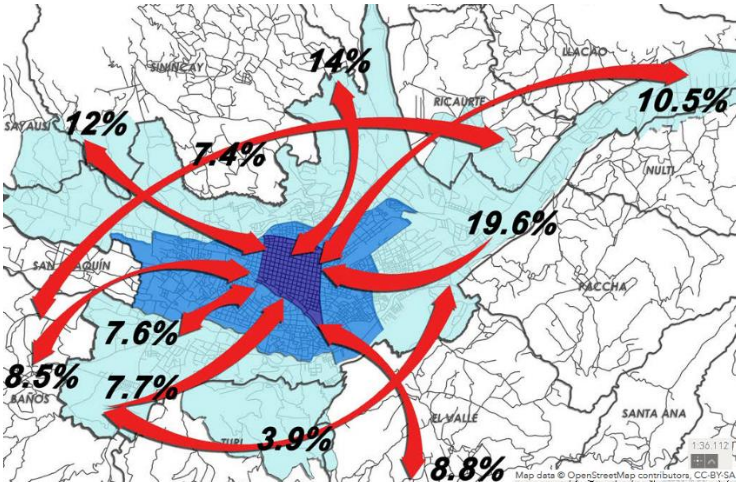

Figure 2. Relation of the location of the destination in vehicular mobility.

The demand management methodology for recharging EVs is evaluated in the city of Cuenca with information that comes from actual variables of the case study, both from mobility patterns and EV battery charge and discharge curves, as well as radiation patterns to determine the efficiency of the PVG. However, the methodology is generic and could be implemented in areas with similar conditions, meeting criteria and regulatory aspects and variables of the study area so that the generation and demand infrastructure is technically, economically, and environmentally sustainable.

2.1. Regulatory Aspects—Ecuadorian Electricity Sector

Under these considerations, the regulatory aspects become an integral part of the investigation since they allow for establishing the technical parameters of operation and financial indicators for the proposed methodology. Next, the main rules and regulations that govern the Ecuadorian electricity market for the PVG and demand management with the incorporation of electric mobility are studied. The Agency controls the regulations for the Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR).

2.1.1. Regulation ARCERNNR 001/2021—Distributed Generation

This regulation aims to determine the terms and conditions for the qualification, connection, installation, and operation of electrical systems of distributed generation with renewable energies for the supply to consumers [19]. The most relevant aspects of this regulation for research are:

- Generation must maintain a nominal power of less than 1 MW.
- The system has to be connected in sync with the distribution networks.
- Due to the distributed generation figure, this cannot be greater than the demand, which means that there will only be self-sufficiency (prosumer).

Under this regulation, the peak power of the photovoltaic solar power plant that will inject energy into the network and supply the proposed charging stations is determined, which was set at 1 MW.

2.1.2. Regulation ARCERNNR 005/20—Transactions in the Ecuadorian Electricity Market

It constitutes the provisions and regulations for the commercialization and administration of commercial transactions for wholesale participants in the Ecuadorian electricity sector [21]. The relevant aspects of the investigation are:

- Large consumers and self-generators will pay the transmission cost associated with power and distribution tolls to the transmitter and utility.
- Commercial transactions for projects with rated power less than 1 MW will be settled by the provisions of the distributed generation regulation and this regulation.

2.1.3. Fee Schedule for Marketing to Regulated Customers

A document issued by ARCERNNR establishes the electricity tariffs for the different types of customers, which may be residential with low-voltage electricity consumption or an industrial nature for activities with large electricity consumption such as businesses, industry, and the provision of public services as private users in medium and high voltages [22]. With this and the previous regulation, the base costs that will be charged for a recharge of an EV will be established according to time ranges for the project's profitability.

2.2. Mobility Behavior Patterns and Forecast of EVs

2.2.1. Surveys

The survey looks for patterns of use for resupply by users who have ICEVs. It is intended to obtain a general panorama and extrapolate to a scenario where EVs replace said vehicles. According to the Ecuadorian Motoring Agency (AEADE), the province of Azuay in 2020 had 137,700 light vehicle units [23]. This information calculates the statistical sample size for the analysis expressed in Equation (1).

$$Sample\ size = \frac{\frac{Z^2 * p(1-p)}{e^2}}{1 + \left(\frac{z^2 * p(1-p)}{e^2 N}\right)} \tag{1}$$

where:

N: Population size

e: margin of error

z: z-score

p: variability

Equation (1) determines the sample size, whose result was to survey 1059 people from the locality; the results ensure a margin of error of 0.03% and a confidence level of 95%. However, a sample of 1080 respondents belonging to the city of Cuenca and its surroundings was taken, and the application of the surveys was carried out online and in person. The selected questionnaire consisted of 12 questions divided into two sections, eight focused on knowing the habits of use and frequency of refueling of conventional cars, and four focused on the acceptance of the EV.

The results obtained in the survey show that a large percentage of the respondents state that use of their vehicle was for personal reasons, followed by uses related to their work, and finally public transport; additionally, in Cuenca, being an intermediate city, the average distance travelled by the respondents per day is around 10 to 50 km, as indicated in Figure 3.

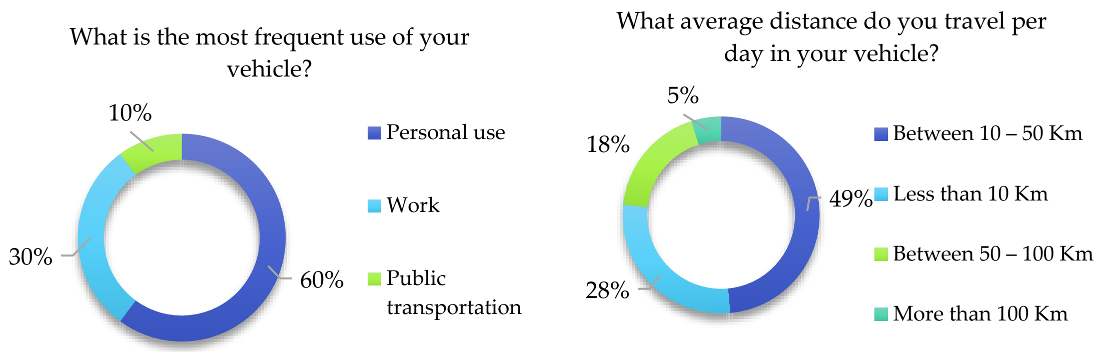

Figure 3. Distance travelled by users.

The habits at the time of refueling the vehicles of the surveyed population are very marked, with a predominance of refueling when the indicator level is below its average; this refueling is mainly done with gasoline, as shown in Figure 4.

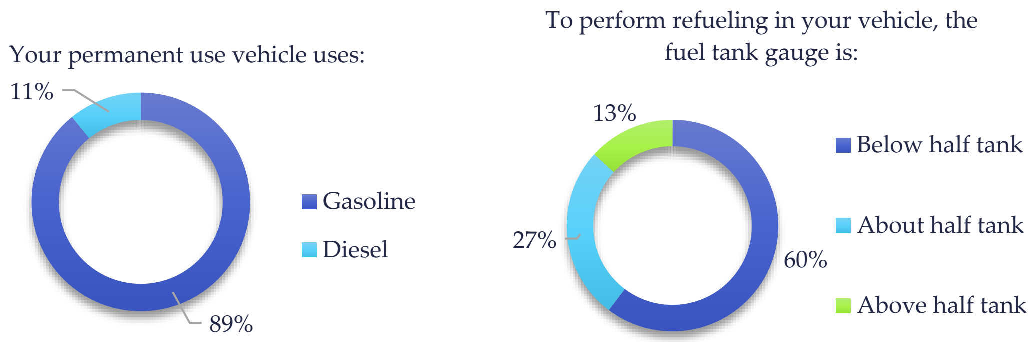

Figure 4. Fuel level for the next recharge.

The surveyed population prefers to refuel their vehicle weekly in terms of frequency, hours, refueling time, and monthly budget. From 8:00 a.m. to 10:00 p.m., the average time they spend at the fueling station is 5 to 10 min; and the monthly budget allocated by users is from USD 20 to 50, and the detail is indicated in Figures 5 and 6.

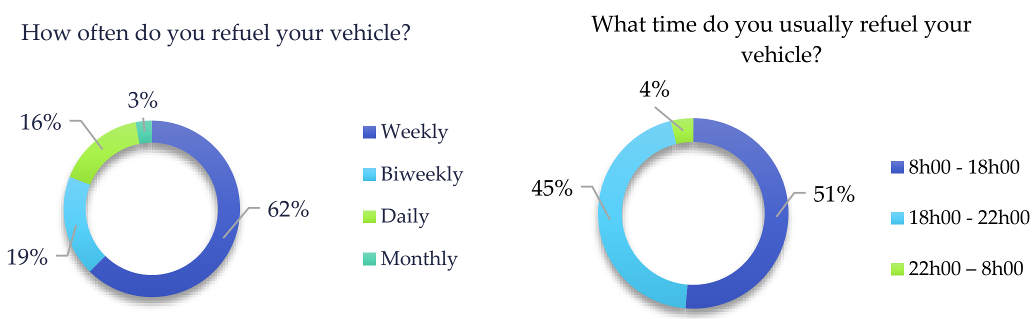

Figure 5. Supply frequency-hours.

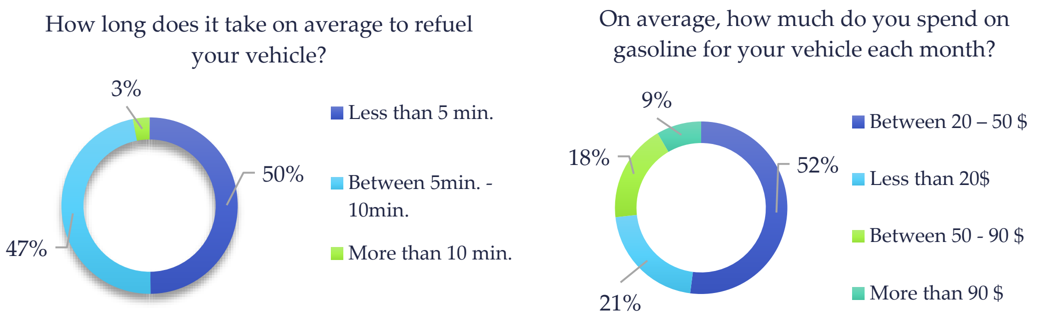

Figure 6. Supply time—monthly budget.

Regarding the acceptance of EV technology, the population of respondents state that 78% are interested in acquiring an EV. However, 73% are unaware of the advantages or tariff exceptions that the government provides for using an EV, which could be reflected in the low number of EVs present in the city, as indicated in Figure 7.

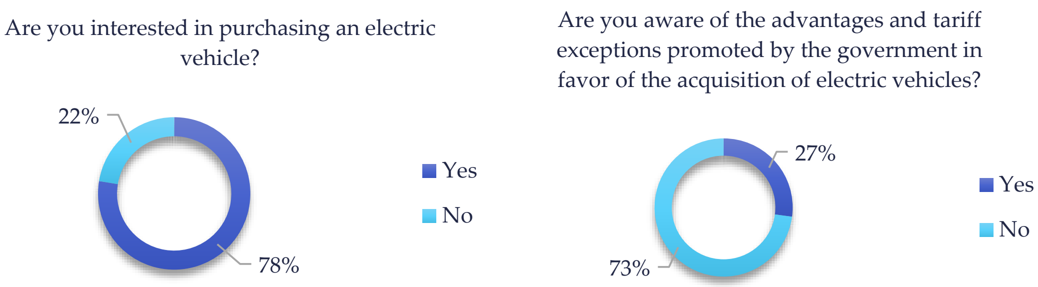

Figure 7. Acceptance of EVs—knowledge of laws.

The factor that worries citizens most when purchasing an EV is the availability of charging points, as reflected in Figure 8. Another factor that worries citizens is the battery duration and autonomy since replacing a battery would represent a considerable expense and might not be profitable for some users.

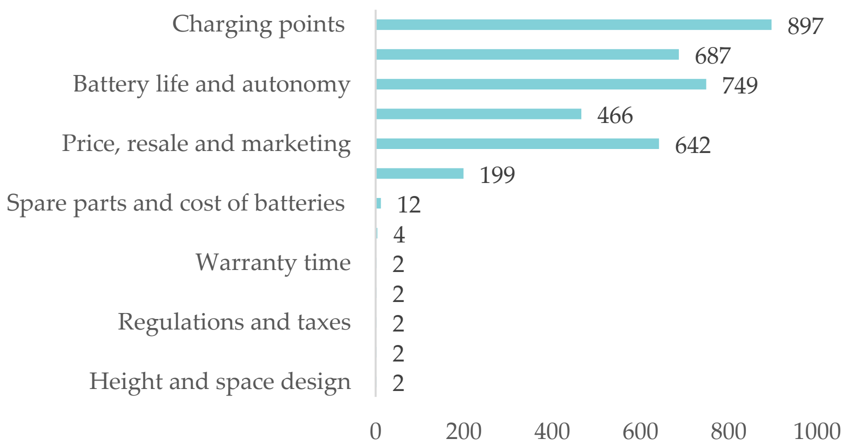

Figure 8. Reasons that concern users before purchasing an EV.

According to the citizens surveyed, the most convenient place to recharge if owning an EV is at home. There is also a high number of citizens who prefer to recharge their EVs at public charging points through charging stations (see Figure 9).

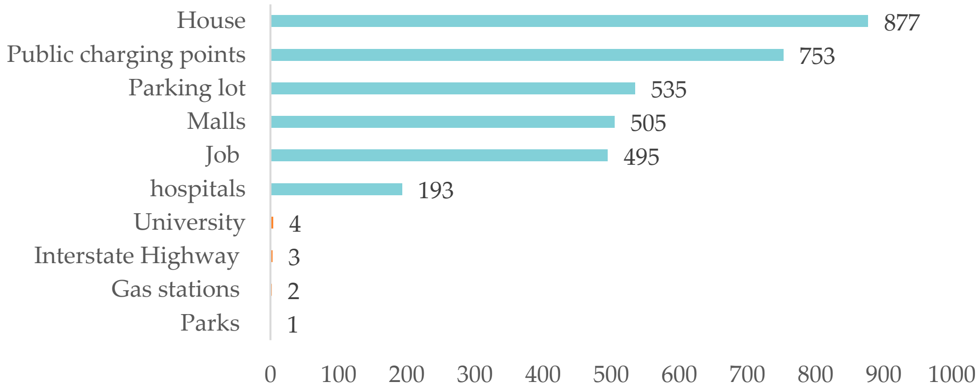

Figure 9. Preferred places by users for EV recharges.

2.2.2. Projection of EVs Case Study in the City of Cuenca

Based on the register of commercialization of motor vehicles in Ecuador, the sale of light internal combustion vehicles in 2021 reached the figure of 100,369 units, compared to 280 EV units sold, which represents 0.28% of the total cars marketed this year, as cited in [23].

Estimates made by the US consulting firm "Frost and Sullivan" indicate that by 2025 hybrid electric vehicles, plug-in hybrid electric vehicles, and battery EVs could reach 14,950 units; this would represent the highest level of penetration in the region with 9.9% of total vehicle sales in the country [24].

The demand estimation is generally carried out in different models; one is the approximation of the demand for EVs under a trend line obtained from previous data regarding the sale of EVs in Ecuador. There is a record of vehicle sales in the country since 2015, although, for practical purposes, it was taken from 2016 since, in 2015, only six units were sold [25].

According to data presented in [25,26], the city of Cuenca has a record of approximately 85 commercialized EV units; the trend line is adjusted to a third-degree polynomial function, as shown in Figure 10. The adjustment of the curve allows the third-degree equation to estimate the number of EVs entering the vehicle fleet yearly until 2050.

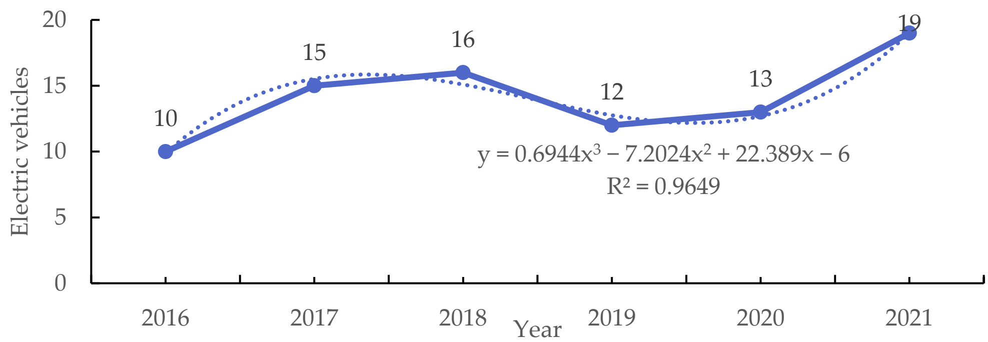

Figure 10. The trend line for the projection of EVs in the city of Cuenca [24,25].

The annual growth projection of EVs in Cuenca is shown in Figure 11; this estimate predicts that in the year 2050, there will be approximately 182,114 EV units in circulation. The curve tends to be exponential in its growth from the year 2026.

Figure 11. EV growth forecast until 2050 in the city of Cuenca.

2.3. Analysis of the Meteorological Variables for Photovoltaic Solar Generation

Ecuador has a predominance of renewable energies for electricity generation, with 60.73% of the 5,299 MW installed power coming from renewable energies such as hydro with 58.44%, wind with 0.24%, photovoltaic with 0.32%, biomass with 1.65%, and biogas with 0.08% [27,28].

In [29], The "Solar Atlas of Ecuador for electricity generation" is presented; this study determines that the average value of global solar irradiation in Ecuador is approximately 4575 Wh/m^2/day.

Projects that include renewable energy have been widely promoted in recent years, and this is because the country is located in a privileged area with excellent potential for electricity generation; however, according to the study presented in [30], reform of the Ecuadorian legal framework is needed in terms of energy, which includes incentives for the installation of distributed generation by residential, commercial, and industrial clients through renewable energy systems such as photovoltaics.

The area in which the study case is located [31,32] is in the province of Azuay, Canton Santa Isabel; in this area, it was determined that the average daily radiation is 5.22 kWh/m^2/day. For the analysis, the PVsyst computational tool was used with updated meteorological variables.

In [33], a design and feasibility study of a photovoltaic plant connected to the network for self-consumption with a nominal power of 1 MW is carried out; the results obtained from this research are taken as a reference to adapt them to the topographical and climatological conditions of the Azuay province. The chosen solar panels, YL280P-35b model, are manufactured by Yingli Solar, while the PVS800-57-0250kW-A inverter was made by ABB.

Once the simulation was carried out, a database was compiled corresponding to daily photovoltaic solar generation curves for one year. They are available in PVsyst through Meteonorm software. Figure 12 shows the daily generation curves where it is observed that throughout the year, this curve varies according to the seasonal climatic conditions of the place.

Table 2 shows the projected values of energy injected into the network corresponding to each month during the year. February is the month with the lowest energy production, with 111.5 MWh injected into the network, while May is the month with the highest generation, with 144.3 MWh injected into the network. The total energy projected to be injected is also shown.

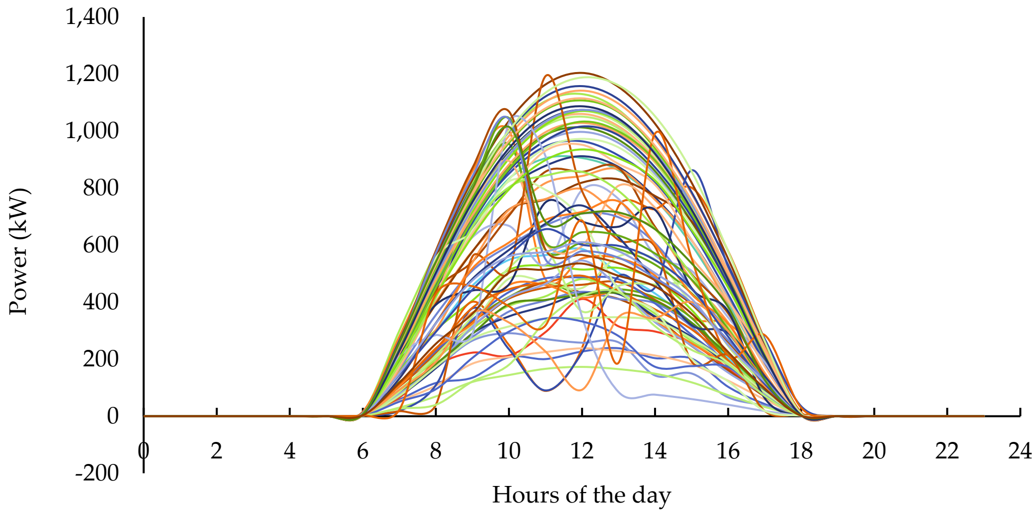

Figure 12. Daily generation data over a year of the photovoltaic solar power plant.

Table 2. Summary of simulated parameters for photovoltaic solar generation.

Month	Global Horizontal Irradiance (kWh/m^2)	Horizontal Diffuse Irradiation (kWh/m^2)	Temperature (°C)	Energy Injected into the Network (MWh)	Performance Ratio PR
January	173.6	67.74	21.3	132.4	0.818
February	140.6	72.87	21.54	111.5	0.823
March	171.2	75.66	21.86	138.6	0.815
April	165.8	72.72	21.49	140.2	0.82
May	165.2	53.86	20.82	144.3	0.816
June	150.5	62.24	19.05	135.8	0.836
July	155.4	65.38	18.31	139.7	0.839
August	162.2	68.59	17.83	141.8	0.839
September	167.9	64.7	17.66	141.2	0.832
October	142.4	81.74	18.11	116.7	0.841
November	151.2	70.22	18.48	118.3	0.831
December	159.4	76.7	20.22	123	0.829
Year	1905.4	832.42	19.72	1583.5	0.828

With the simulation data and the generation parameters [32], the estimated costs for the construction of the PVG plant are obtained with a total investment of USD 1,874,589 and annual operation, maintenance, and administration costs of USD 58,550.

In the same way, the estimated costs for the charging stations are based on the implementation costs of this technology as presented in [34]. According to the technical standards in [35], the implementation costs of five charging stations with Raption50 chargers amount to USD 1,024,380. Among the main characteristics of electric vehicle chargers, Raption50 [36] highlights its adjustable charging power, which makes it an ideal technology when managing demand and delivering charging power to different types of electric vehicles.

In [37], the most convenient places for the location of fast charging stations in the city of Cuenca are determined through the hierarchical analytical process (AHP). The ideal places taking into account criteria such as accessibility, security, and preference by users, are specific sectors such as Mall del Río and Millennium Plaza; in terms of criteria such as power in distribution networks, the places proposed in the investigation are the Regional Hospital, Monay Shopping, and CELEC.

3. Methodology

It consists of permanently supplying the electrical energy demand of a number "m" of recharging stations considering the EV penetration rate and the coincidence in recharging times, using photovoltaic solar renewable energy, through transactions in the local electricity market. This energy will be delivered to the distribution network during the daytime hours between 6h00 and 18h00. The use of storage systems such as batteries is not considered since the energy generated will be injected and absorbed directly from the network to be settled monthly in the electricity market.

The fundamental operating parameters for the start-up of a photovoltaic plant are obtained using the "PVsyst" computational tool and the meteorological variables available in "Meteonorm" software for the study area.

Consumers' behavior patterns and refueling preferences are determined through surveys and predictive tools; in this way, it will be possible to obtain the variables and magnitudes of energy consumption for recharging EVs. An approximation will determine the EV sales estimation each year during the project's useful life under a trend line obtained from EV data from previous years in Ecuador.

With the generation and demand variables, a linear optimization model is built using the "GAMS" computational tool. For a particular time, "k", in which the energy generated by the photovoltaic solar plant injected into the network is less than the energy consumed by the demand present in the charging stations, the purchase of power from the utility is considered with a penalty cost carried over to the total cost.

Electric vehicle users who need to use the charging station can choose between regulated and unregulated charging. The regulated charging mode will determine the power available for a time "k", limited between a minimum and maximum charging power. The user who chooses this option will benefit from economic incentives at lower energy costs. The second way of recharging is the non-regulated one; the user will recharge the EV at the maximum charging power or the one they prefer. The energy cost will be much higher than the regulated charge. In this way, the optimization methodology reduces demand peaks, reducing the impact on distribution networks.

Figure 13 shows the summary of the methodology for managing the demand for electrical energy for recharging electric vehicles through dispersed photovoltaic solar generation.

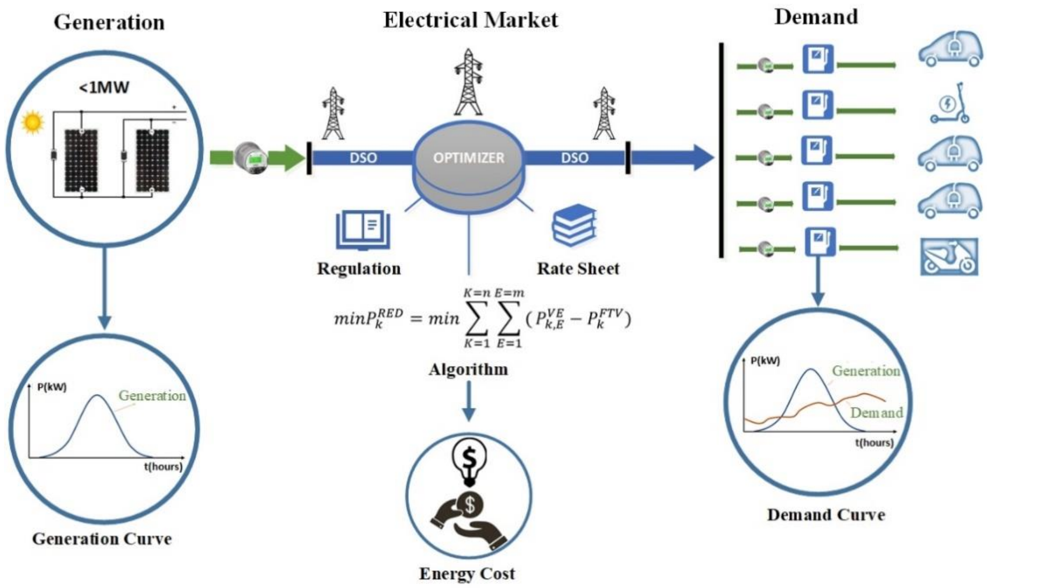

Figure 13. Methodology for demand management in recharging EVs.

3.1. Analysis of the Methodology in Scenarios with Recharge Variables and Hours of Use

For the development of the methodology, an infrastructure was modelled that uses 20 charging stations or bays to supply energy to the EVs that enter the distribution system of the utility. The occupancy percentage corresponds to the randomly available charging spaces 24 h a day, based on the K instants in 15-min intervals and the number of charging stations.

The research proposes three different scenarios of occupancy of the charging spaces, 30%, 60% and 80%, respectively, randomly based on availability, since a 100% occupancy would mean that 1,920 charging spaces are used over 24 h. The result is explained in Table 3.

Table 3. Summary of the tests carried out with an hourly rate.

Time Range	N° K Periods	N° Station (u)	N° Places 100% (u)	N° Places 30% (u)	N° Places 60% (u)	N° Places 80% (U) (u)
22h00–8h00	36					
8h00–18h00	44	20	1920	576	1152	1536
18h00–22h00	16					

Note: This shows the number of places available over 24 h with the parameters established according to the occupancy percentage.

On the other hand, the research uses the time slots of the tariff schedule for users connected to medium voltage (600 V < 34 kV) and to high voltage (34 kV < 69 kV).

Scenario 1: Occupancy of 30% of the recharging places. This scenario proposes an occupation of 30% of the recharging sites available over 24 h, that is, 576 places. The behavior patterns for the recharging schedule are based on the surveys carried out, where the schedules in which the users of combustion vehicles tend to resupply their vehicles were determined.

On the other hand, under the same percentage of occupancy of charging places, a modification to the charging patterns by users with an ideal load distribution is proposed, which would improve the results in terms of taking advantage of photovoltaic generation, and less effect on the network, as shown in Table 4.

Table 4. Case with 30% occupancy of the charging bays.

Time Range	K Time Periods	30% Occupation	Surveyed	Ideal
22h00–08h00	36		4%	30%
08h00–18h00	44	576	51%	50%
18h00–22h00	16		45%	20%

Scenario 2: 60% occupancy of cargo spaces and a 60% occupancy of charging places are proposed; however, taking the charging pattern of the users of combustion vehicles surveyed, in the time range of 6h00 p.m. to 10h00 p.m., it could not satisfy the demand for charging places, because 518 spaces are required, and only a total of 320 are available. In this case, the distribution of ideal load patterns is proposed, as in the previous case cited in Table 5.

Table 5. Scenario with 60% occupation of the charging bays.

Time Range	K Time Periods	60% Occupation	Surveyed	Ideal
22h00–08h00	36		4%	30%
8h00–18h00	44	1152	51%	50%
18h00–22h00	16		45%	20%

Scenario 3: Occupancy of 80% of the loading places presents the same problem as the previous case; a redistribution of occupancy percentages of loading spaces is proposed. In this way, the occupancy is increased in the time range of 22h00–08h00 and significantly decreases in the hours of 08h00–22h00 occupancy percentage, as shown in Table 6.

Table 6. Scenario with 80% occupation of the charging bays.

Time Range	K Time Periods	80% Occupation	Surveyed	Ideal
22h00–8h00	36	1536	4%	35%
8h00–18h00	44		51%	50%
18h00–22h00	16		49%	15%

3.2. Mathematical Formulation

The model proposes the supply of electrical energy to a number of stations, "m", or charging bays through distribution networks. This network will assume the generation injected by the photovoltaic solar plant. In case the demand exceeds the age, the purchase of energy from the utility under penalty costs will be considered. The equation expresses the energy balance between generation and demand:

$$P^{NS} = P^{VE} - P^{GSFV} \tag{2}$$

The power not supplied by the photovoltaic solar plant (P^{NS}) will be equal to the difference between the power consumed by electric cars (P^{VE}) and the power generated by the photovoltaic solar plant (P^{GSFV}). Obtaining a positive balance will mean that energy must be purchased from the utility at the cost of the regulated market under the tariff schedule to cover the demand at the charging stations; on the other hand, if said balance is negative, it will mean that more than what is demanded is being generated, and these surpluses may be used at times of non-generation or the end of the monthly energy balance.

The electrical energy supply is permanent throughout the day and is divided into periods called instants "k". Each instant of time "k" has a lapse of 15 min, so the number "n" of instants "k" will be 96 over 24 h in the set of time *T*.

$$T = [1,\ 2,\ 3, \ldots,\ n] \tag{3}$$

The total power consumed by the EVs will depend on the load power of each vehicle of the set "*VE*" represented by the expression $P^{VE}_{k,E}$. This variable is two-dimensional due to the variation as a function of time "*k*" and the station to which "*E*" is connected.

$$P^{VE}_{k,E} = \begin{bmatrix} P^{Ve}_{1,1} & P^{Ve}_{1,2} & \cdots & P^{Ve}_{k1,m} \\ P^{Ve}_{2,1} & P^{Ve}_{2,2} & \cdots & P^{Ve}_{k2,m} \\ \cdots & \cdots & \ddots & \cdots \\ P^{Ve}_{n,1} & P^{Ve}_{n,2} & \cdots & P^{Ve}_{n,m} \end{bmatrix} \tag{4}$$

The power generated by the photovoltaic solar power plant is not constant. It varies according to the generation curve, so there would be different powers throughout the day or at each instant "*k*" of time.

$$P^{GSFV}_{k} = \begin{bmatrix} P^{G}_{k1} \\ P^{G}_{k2} \\ \cdots \\ P^{G}_{kn} \end{bmatrix} \tag{5}$$

By adding all the powers over time, the objective function of the model is represented as follows:

$$P^{NS}_{k} = P^{VE}_{k,E} - P^{GSFV}_{k} \tag{6}$$

The model minimizes the purchase of energy from the distributor for power not supplied due to the lack of generation of the photovoltaic solar plant as a result of the energy demand for recharging EVs by increasing power consumption and the development of photovoltaic solar generation.

$$minP_k^{NS} = min \sum_{K=1}^{K=n} \sum_{E=1}^{E=m} (P_{k,E}^{VE} - P_k^{GSFV}) \quad (7)$$

Defined as:

$$P_{k,E}^{Ve} = C_{k,E} \times PX_{k,E} \quad (8)$$

Matrix $P_{k,E}^{VE}$ will be equal to the product of the binary matrix resulting from the linearization of $P_{k,E}^{VE}$ by the matrix of decision variables $PX_{k,E}$

$$\overline{P^{VE-min}} < P_{k,E}^{VE} < \overline{P^{VE-mx}} \qquad \forall\ P^{VE} \in VE \quad (9)$$

The regulated power cannot be greater than the maximum charging power of the electric vehicle that enters the system. On the other hand, said power may not be less than a minimum load assigned by the operator to consistently deliver electricity to users regardless of whether a regulated or unregulated load is chosen.

$$P_k^s = \begin{bmatrix} P_{k1}^s \\ P_{k2}^s \\ \ldots \\ P_{kn}^s \end{bmatrix} \quad (10)$$

By not considering a physical energy storage system for the photovoltaic solar power plant, in moments when energy is not generated, energy must necessarily be purchased from the utility and said consumption could be restricted to a maximum power value (P_k^s) defined by the operator and be variable over time.

$$P_k^s \geq \delta \quad \forall\ k \in T \quad (11)$$

By restricting the value of $P_{k,E}^{VE}$ to a minimum value ($\overline{P^{Ve-min}}$), the value of P_k^s must necessarily be greater than or equal to "δ" at each instant "k" due to the number of loading stations or bays. It would be the minimum value the system must restrict to for energy security in case of photovoltaic solar plant failure or for non-generation at night.

$$P_k^{GSFV} + P_k^s \geq P_k^{VE} \qquad \forall\ k \in T \quad (12)$$

The sum of the restriction power purchased from the utility (P_k^s) and the generation power (P_k^{GSFV}) must be greater than or equal to the regulated power produced by recharging EVs at charging stations.

4. Model Simulation Settings

Knowing the decision variables, the equations that govern the system and its restrictions, it is possible to extrapolate the model to a simulation environment in the GAMS programming language. The proposed scenarios indicate how the EVs enter at each moment "k", with a maximum of 96, and at each charging station "E", with a maximum of 20 bays.

The maximum power at which each bay allows charging is 50 kW, a limitation of the charging stations. Additionally, the minimum power, regardless of the total capacity with which the vehicle is loaded, will be 7.2 kW; this would be the minimum power that the optimizer would assign, with which the value of "δ" for the vector P_k^s will be 144 kW in hours of no-generation, and from 6:00 p.m. to 10:00 p.m. and 10:00 p.m. to 6:00 a.m., a power of 300 kW will be assigned to the vector P_k^s so as to restrict the charging power to a lesser extent and encourage use at these times.

The simulation configuration for the power data entry is carried out randomly, respecting the percentages of maximum and minimum demand according to the load schedule.

The programming environment in GAMS will have two matrices, one that represents the load powers that are entering the system ($P^{VE}_{k,E}$) and another binary-type matrix ($C_{k,E}$) resulting from the linearization of $P^{VE}_{k,E}$ that will indicate whether or not the entered electric vehicle is being charged.

$$P^{VE}_{k,E} = C_{k,E} \times PX_{k,E} \begin{bmatrix} P^{Ve}_{1,1} & P^{Ve}_{1,2} & \dots & P^{Ve}_{1,m} \\ P^{Ve}_{2,1} & P^{Ve}_{2,2} & \dots & P^{Ve}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ P^{Ve}_{n,1} & P^{Ve}_{n,2} & \dots & P^{Ve}_{n,m} \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 0 \\ 1 & 0 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 0 \end{bmatrix} \times \begin{bmatrix} PX_{1,1} & PX_{1,2} & \dots & PX_{1,m} \\ PX_{2,1} & PX_{2,2} & \dots & PX_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ PX_{n,1} & PX_{n,2} & \dots & PX_{n,m} \end{bmatrix} \quad (13)$$

The optimization program multiplies the binary matrix by a power $PX_{(K,E)}$. The constraint Equations (8)–(12) return a matrix of optimized powers that regulate the charging capacity of the vehicles that enter. The power matrix constrains the maximum load values the optimizer will assign to each car $P^{VE}_{k,E}$.

The recharge power values for the different EVs will be entered randomly, following a homogeneous distribution. These powers have been considered considering some of the best-selling electric vehicles in Ecuador in recent years and worldwide. Table 7 summarizes the main characteristics of the study's chosen electric vehicles, whose recharging powers are significant for each station since these models have different capacities.

Table 7. Characteristic powers of the main EVs in the study.

Mark	Model	Charging Power (KW)	Battery Capacity (KWH)	Autonomy (km)
KIA	Soul EV	50	27	200
NISSAN	Leaf	50	40	270
BYD	E2	22	35.2	305
BYD	S2	22	42	400
BYD	E5	22	60.4	400
BYD	T3	22	48	250
MG	ZS EV	28	44.5	335
RENAULT	ZOE	7.4	52	395
FIAT	500	11	23.8	180
VOLKSWAGEN	ID.4	50	82	418
PEUGEOT	10^{-208}	28.7	50	340
HYUNDAI	KONA	50	39.2	305
VOLKSWAGEN	ID.3	45	11	330

For the analysis, average generation values are taken, as shown in Figure 14, corresponding to a day of random generation.

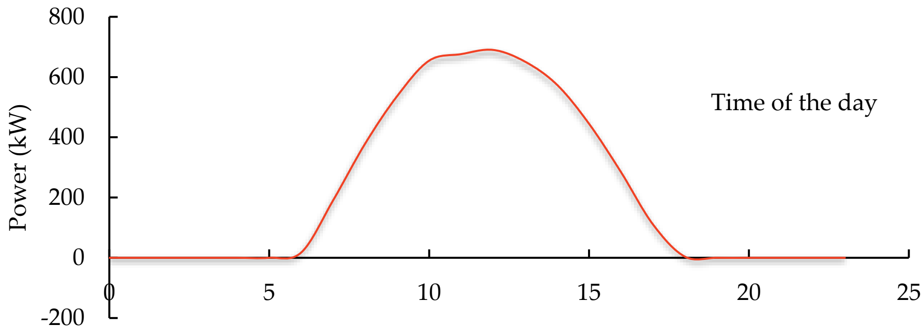

Figure 14. Average generation values for the photovoltaic solar power plant for simulation configuration.

5. Results

When simulating the model in the GAMS program, the optimized and non-optimized power curves are obtained due to EV recharging demand and the photovoltaic solar generation profile.

5.1. Scenario 1: Occupancy of 30% of Cargo Spaces

The energy injected into the grid by photovoltaic solar generation supplies demands without complications, except during peak demand hours from 6:00 p.m. to 10:00 p.m., with fewer recharging places, as shown in Figure 15. Of all the recharges at a maximum power of 144 kW between 6:00 p.m. and 10:00 p.m., the power that the photovoltaic solar plant could not supply must be purchased from the utility at the cost of the electricity market. The objective of the methodology is to provide the most significant amount of energy to the EVs with the least impact on the network. Under this scenario, for the users who do not have time to recharge, the model should modify the charging patterns, distributing the demand during the day and avoiding saturation and demand peaks at specific times—an ideal scenario.

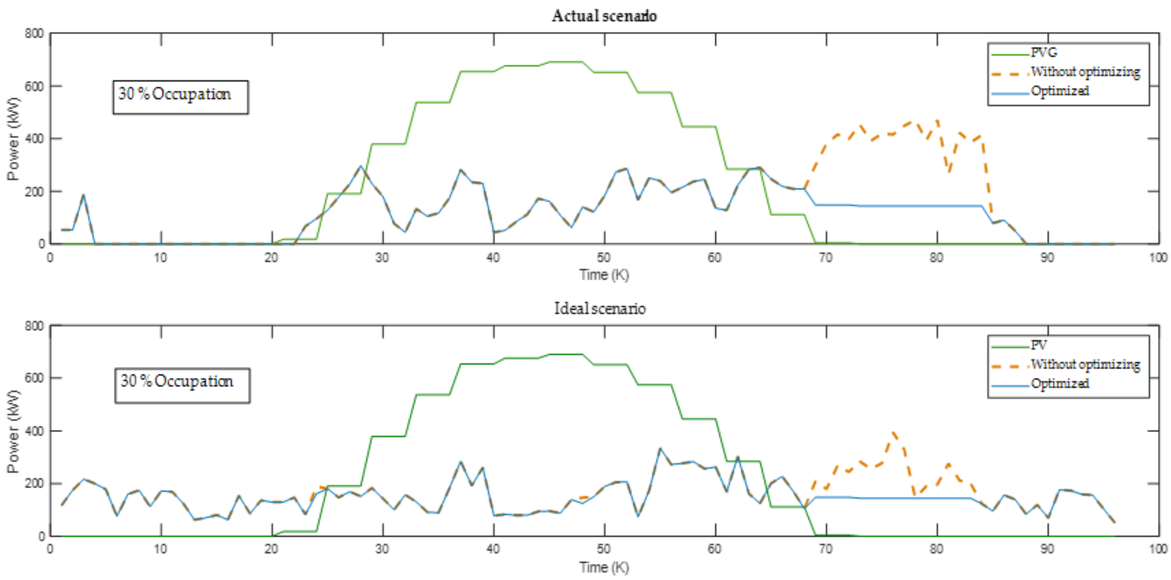

Figure 15. Demand optimization in the 30% scenario (real and ideal load patterns).

The modified scenario proposes, like the first one, occupation of 30% of cargo spaces but distributed homogeneously. Figure 15 shows the optimized power and unoptimized power.

In all the scenarios proposed, it is assumed that the users agree with the energy that the optimizer supplies them in a specified time without requesting more recharging.

5.2. Scenario 2: Occupancy of 60% of Cargo Spaces

By replicating the analysis of 60% occupancy of the charging bays, the charging patterns according to the surveys cannot be simulated due to the large percentage of recharges in peak hours, 18h00 to 22h00, the available charging stations or bays do not satisfy demand, therefore, recharges necessarily have to be reconfigured to times with less demand. The scenario with 60% occupancy of the charging bays and ideal charging patterns is reflected in Figure 16.

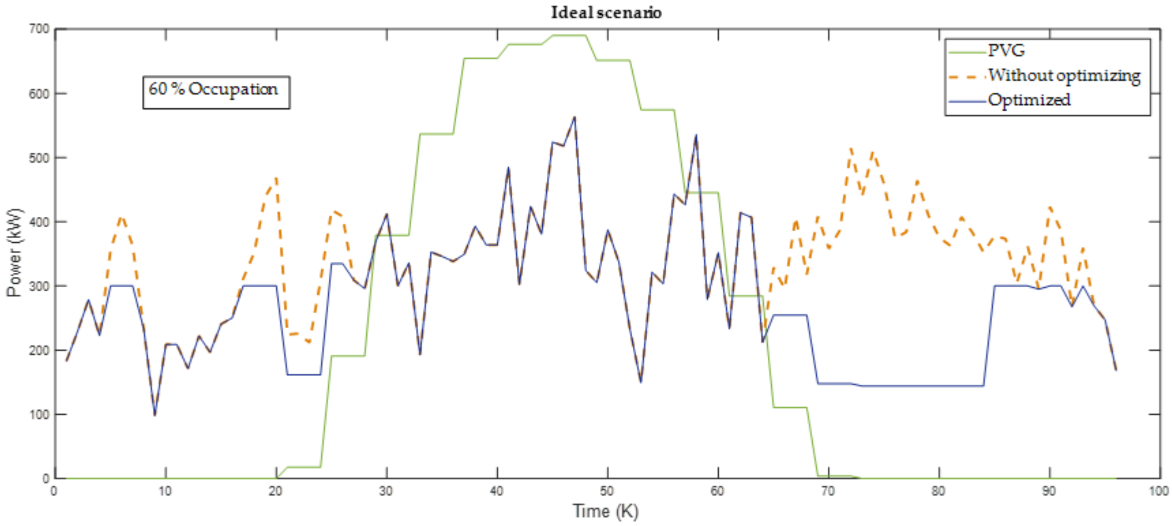

Figure 16. Demand optimization in the 60% scenario (real and ideal load patterns).

As the load is more significant, the optimizer must restrict the demand more frequently, with peaks of 300 kW during times without generation and 144 kW during times of high need, as in previous cases. Thus, demand peaks that exceed generation even in the optimized scenario are also observed because, at each instant of time "k", the optimizer assigns an extra 144 kW power added to the generation.

5.3. Scenario 3: Occupancy of 80% of Places for Recharging EVs

The scenario with 80% occupancy does not differ from the case of 60%; photovoltaic solar generation supplies to a lower percentage of load occupancy spaces. In this scenario, it can be seen that the demand curve tends to be similar to the power curve P_k^s and P_k^{GSFV}, since the optimizer must more frequently restrict the load power $P_{k,E}^{VE}$, it is due to high demand, as demonstrated in Figure 17.

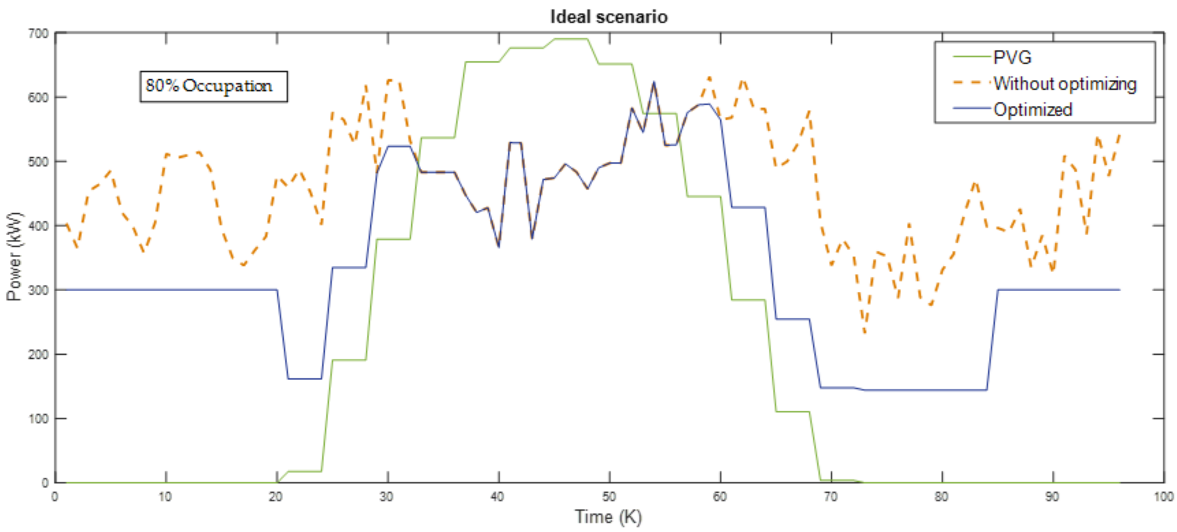

Figure 17. Demand optimization in the 80% scenario (real and ideal load patterns).

Similarly, the model buys energy from the utility when there is a negative balance between generation and demand. The power not used from photovoltaic solar generation is significantly lower than in other scenarios.

Making an accurate forecast, which indicates the limit in the percentage of occupancy placed in the recharging bays so that the photovoltaic generation system supplies, is highly uncertain because the powers that enter the system is random and changes frequently. Despite this, based on tests, this percentage ranges from about 45% occupancy.

By restricting the charging power of the EV in the case of the optimized scenario, the energy supplied will be less; however, if said demand is distributed throughout the day, as is the point in ideal cases, the power provided in an optimized scenario does not differ significantly from the non-optimized method. The detail of the analysis is shown in Figure 18.

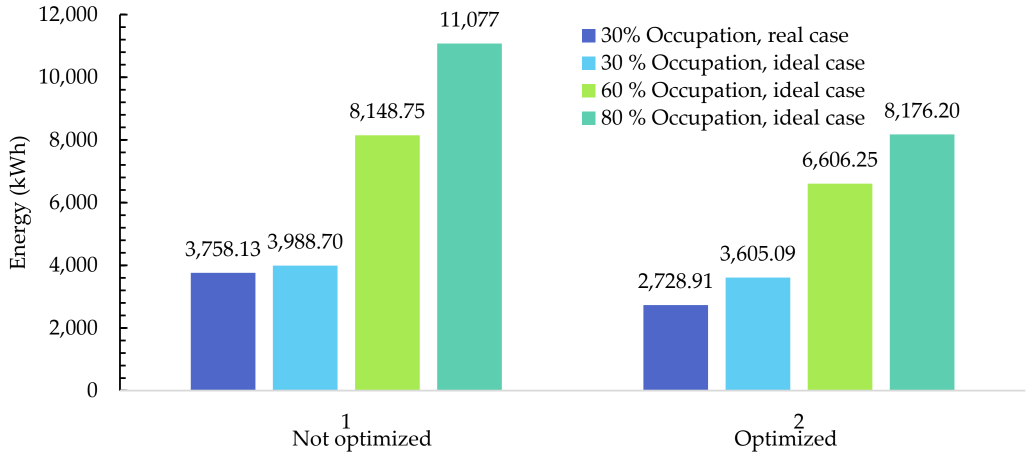

Figure 18. The energy supplied as a percentage of occupancy of recharging spaces.

5.4. *Profitability Analysis of the Proposed Methodology*

The input variables are random, and due to their stochastic nature, which causes high uncertainty to be present at the time of executing the algorithm, this makes it impossible to have exact data when performing the profitability analysis under the optimization methodology; however, the response obtained from the scenarios reflects the behavior of the model and the profitability under certain conditions of the project.

The methodology proposes two types of recharging, one in which the user recharges his EV at maximum power with a higher price for the purchase of energy, and the other in optimized recharging, where the charging power is regulated according to the charging conditions demand and market at a lower price.

Figure 19 shows the distribution of costs that should be considered in the final price for energy sales to make the project profitable; being in the first stage, the cost for generation, the following step, costs for distribution related to tolls, commercialization, and expenses for the purchase of energy due to the demand not supplied by photovoltaic solar generation and the last stage comprises the order in which the final recharging costs that the users of the EVs will pay are found.

Under this premise, the economic analysis is configured through the prices set according to the hourly ranges of the medium and high voltage electricity tariffs that govern the tariff schedule and the generation costs per kWh of the photovoltaic solar plant, also considering the toll costs and marketing for energy transport from generation to delivery at charging points. To these prices is added a surcharge or penalty cost for the possible purchase of energy from the utility, which is higher when there is no photovoltaic solar energy injection. In this way, the prices for each type of recharge and each time range are shown in Table 8.

The hours of 06h00–18h00 correspond to the generation hours of the photovoltaic solar power plant and replace the hours of 08h00–18h00 in the tariff schedule. The surcharge or penalty cost is billed when energy is absorbed from the distribution network, regardless of whether or not an optimized recharge is made, so it must be settled with the distributor at the highest rate in the tariff schedule according to regulation 001/2021.

With the recharging costs, an estimate can be made of the price that the user will have to pay for a recharge of his vehicle and the average income that the operator of the charging stations would obtain daily from different percentages of occupancy of recharge parking spaces, with ideal charging patterns and with random charging powers as indicated in Figure 20.

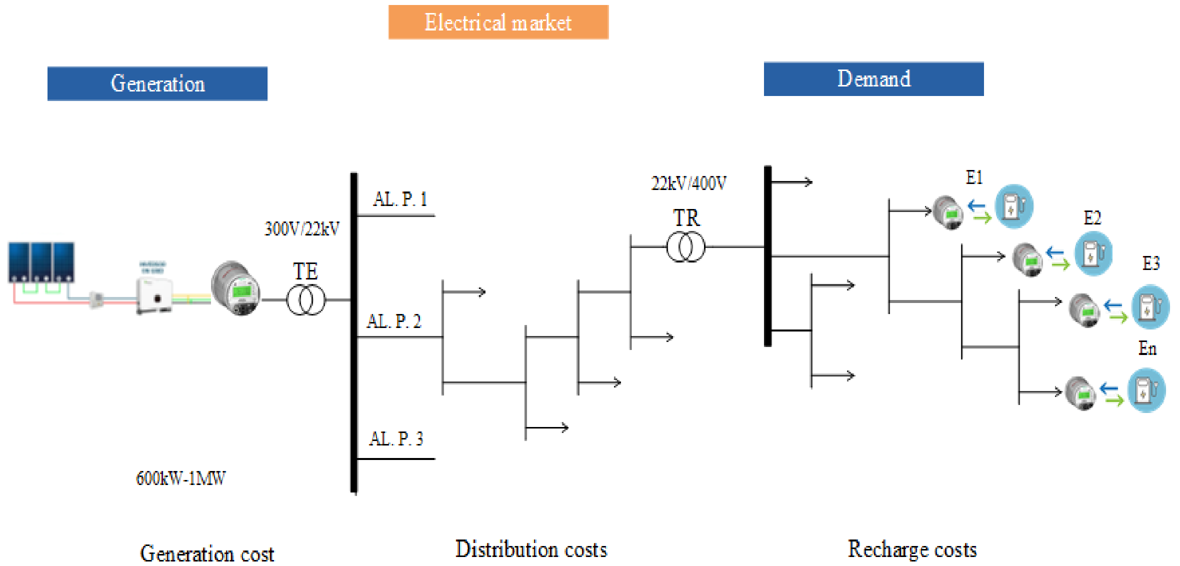

Figure 19. Analysis of costs by stage in the project.

Table 8. Costs for recharging electrical energy with and without optimization.

Schedule	Base Cost	Penalty Costs	Surcharge without Optimization	Cost without Optimization	Cost with Optimization
6h00–18h00	USD 0.18	USD 0.02	USD 0.10	USD 0.30	USD 0.20
18h00–22h00	USD 0.08	USD 0.16	USD 0.10	USD 0.34	USD 0.24
22h00–6h00	USD 0.04	USD 0.08	USD 0.10	USD 0.22	USD 0.12

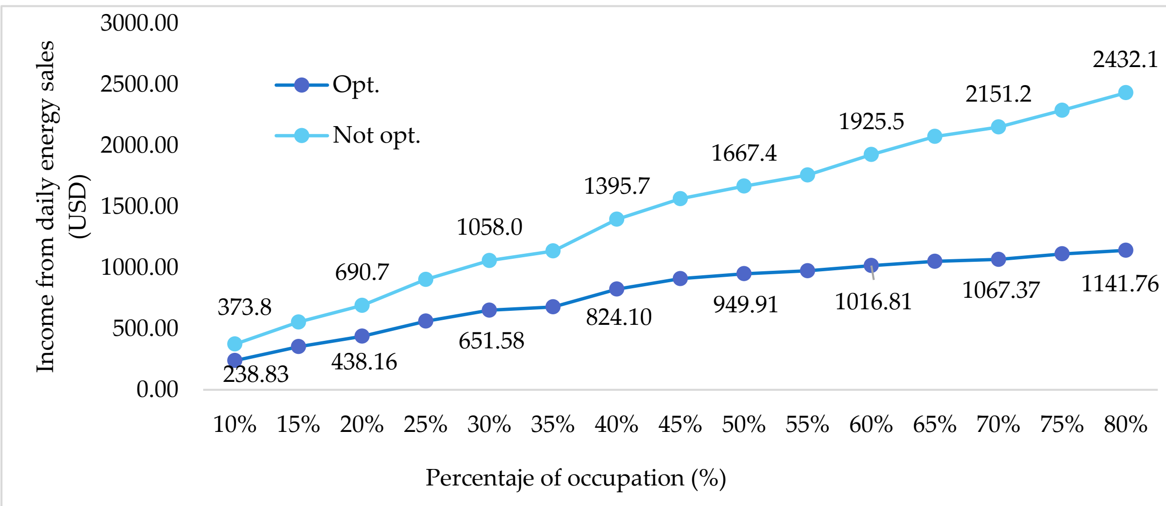

Figure 20. Analysis of costs based on the percentage of occupation and sales.

With the projection of EVs up to the year 2050 and based on the surveys carried out on the population of the city of Cuenca, the percentage of occupancy of recharging spaces for these vehicles at the recharging stations is estimated. The criteria used are based on surveys related to the average kilometers travelled to calculate the number of recharges per month, as well as the percentage of people interested in refueling at public recharging points. In addition, a time of occupancy of spaces for recharging each vehicle, based on an average battery capacity and recharge levels according to the results of the surveys is also calculated.

From the year 2030, under the established parameters, there would be an occupancy of recharging places of 80%. This value is constant in later years since the recharging areas would no longer supply the demand. Its value does not increase to 100% because the recharging places are occupied throughout the 24 h, reflecting reality.

During all the years of useful life of the project, a percentage of variation in the energy production of the photovoltaic solar plant of 0.5% is considered due to the ageing of the solar panels and other components, with which the net income from the sale of energy decreases throughout the useful life of the project with the same percentage of occupancy of charging spaces because more power has to be purchased from the network.

Figure 21 shows the annual income from the sale of energy based on the criteria mentioned as daily income from the sale of energy and percentages of occupation of the annual recharging places throughout the project's useful life.

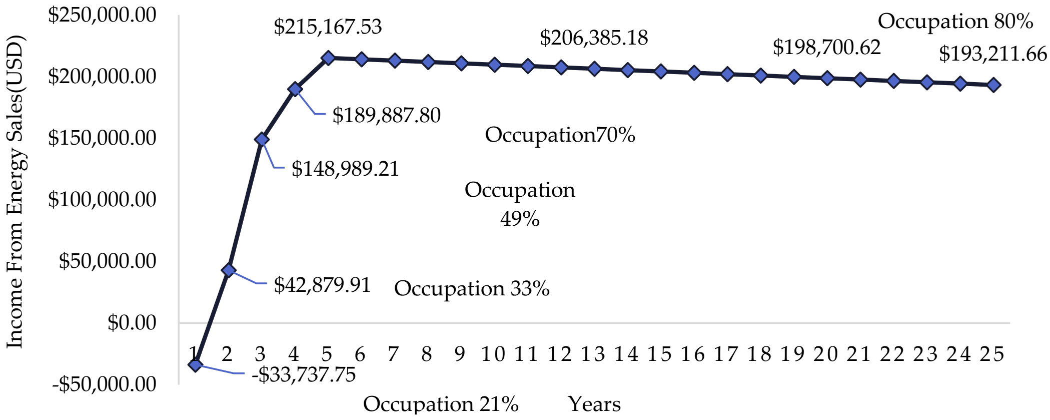

Figure 21. Projection of income according to percentages of occupation of cargo spaces.

Knowing the approximate income from the sale of energy, according to the level of occupation with ideal load patterns, the profitability of the project is estimated, which includes the economic income with the new recharge prices and the expenses for the payment of tolls, commercialization, and costs for the purchase of energy.

The cash flows and the amortization values can be seen in Figure 22. With the values established for EV charging, the recovery period is around 17 years and a return on investment of 60%, with a net present value of USD 1,737,031.50.

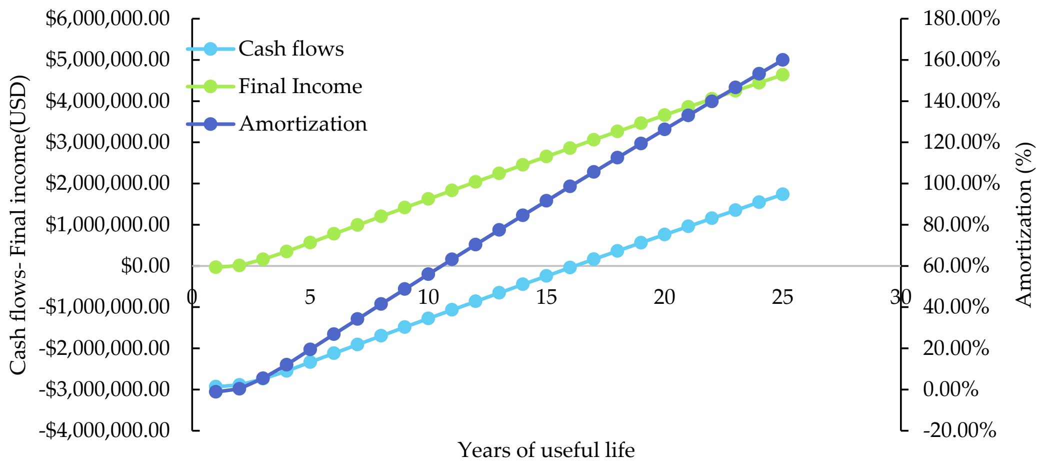

Figure 22. Cash flow, amortization, and total annual income of the proposed methodology.

6. Conclusions

The case study begins with the analysis and determination of mobility behavior patterns based on the surveys carried out in the city of Cuenca-case study-, from which it was determined that the factors that prevent a massive introduction of EVs into the vehicle fleet are the little or no availability of recharging points, in addition to the lack of knowledge and the scarce financial and technological information that involves the replacement of an internal combustion vehicle in front of a traction vehicle with electricity.

Around 70% of the population surveyed is interested in recharging an EV at public charging points, which is why the coming year's research must be carried out based on new regulations and economic incentives that make both public and private investment in electric vehicles attractive to these projects.

In Ecuador, with the new regulations 001/2021 and 002/2021, a wide window of opportunities is open for developing projects with clean and renewable generation. For its part, distributed generation improves reliability and energy security and reduces losses in distribution systems.

The charging patterns obtained through the surveys are viable in the short-term, with a maximum occupancy of 37% of recharging places; from this percentage, the charging designs of users must necessarily be modified to less saturated hours. An ideal distribution of charging patterns under an optimized scenario represents less congestion in the network, which translates into more energy supplied and greater charging power for users who take advantage of this recharge.

The percentage of occupancy of spaces for recharging EVs is based on self-sufficiency through photovoltaic solar generation, in a prosumer concept, to supply demand without maintaining an energy purchase contract in the vertically integrated electricity market. With recurrent payments of distribution tolls to the distribution system operator, representing 45%, this result is a recursive analysis of several randomly chosen scenarios applying homogeneous distribution.

The number of charging stations cannot be less than that established in the model of this research since a smaller number of recharging places would cause financial damage to the period of recovery of the investment and the valuable life of the project with the established economic parameters. Likewise, implementing a more significant number of recharging stations than those specified in the model would put the technical operation at risk. It would not be possible to comply with the regulatory aspects of the project since it would breach the granting of permission for small-scale generation as provided by regulation 001/2021 with maximum renewable power generation of 1 MW.

The use of photovoltaic solar energy to supply the demand at EV recharging stations represents a positive impact on the environment since, being renewable energy, the production chain from generation to consumption closes the cycle in the energy matrix with a significant reduction in CO_2 emissions.

The analysis seeks to technically and financially demonstrate the barriers created against the use of conventional vehicles in such a way that there is a paradigm shift with citizens, and the acquisition of EVs is encouraged to promote the growth of this technology in the short, medium and long-term.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

k	Time frame
E	Cargo bay
Parameters	
$\overline{P^{VE-min}}$	Minimum charging power of the electric vehicle
$\overline{P^{VE-mx}}$	Maximum charging power of the electric vehicle
P_k^s	Minimum load power assigned by the operator in k
δ	Minimum load power value
Variables	
P^{NS}	Power not supplied by photovoltaic solar generation
P^{VE}	Power consumed by electric vehicles
P^{GSFV}	Power generated by the photovoltaic solar plant
$P_{k,E}^{VE}$	The total power consumed by electric vehicles in k, E
P_k^{GSFV}	The power generated by the photovoltaic solar plant in each period k
P_k^{VE}	The total power consumed by electric cars in k
$PX_{k,E}$	Matrix of decision variables in k, E
$C_{k,E}$	Binary type matrix for the linearization of $P_{k,E}^{VE}$
Sets	
T	Set of time intervals k in a day
VE	Electric vehicle

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