# Spatio-Temporal Model to Estimate the Adoption of Rooftop Solar Photovoltaic Systems

R. E. Morales *‡, S. Zambrano-Asanza. **, Alberto Ríos***, Gonzalez-Redrovan J*

*Catholic University of Cuenca, Academic Unit of Posgrate Master's Program in Renewable Energies, Cuenca 010101, Ecuador

** São Paulo State University – UNESP, Department of Electrical Engineering, São Paulo 13506-752, Brazil

*** Technical University of Ambato, Faculty of Systems, Electronics and Industrial Engineering, Ambato 180104, Ecuador

(rommel.morales.45@est.ucacue.edu.ec, sergio.zambrano@centrosur.gob.ec, a.rios@uta.edu.ec, tjgonzalezr@ucacue.edu.ec)

‡ Corresponding Author; Morales R. E, Postal address: Cuenca 010101, Tel: +593 983 334 841,

rommel.morales.45@est.ucacue.edu.ec

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**Abstract-** The trend for renewable energies has motivated residential consumers around the world to have a rapid penetration in the installation of rooftop solar photovoltaic systems. For this reason, power utility companies must plan the inclusion of rooftop solar photovoltaic systems in their distribution grid. The proposed method projects the quantity and location of these systems. The method is divided into 3 modules: temporal, spatial, and potential modules. In the case of the temporal module, it uses census data by dividing the area into districts, and also, it calculates the number of residential customers, which can be converted into rooftop solar photovoltaic systems. On the other hand, the spatial module adjusts the temporal module based on the interaction and spatial influence of neighbours for each district. Finally, the potential module calculates their energy potential according to the geographical location of the districts and evaluates it with the forecast number of customers from the spatial module. The performance of the method is assessed in the service area of an Ecuadorian power utility. The results show that in Cuenca the greatest influence on adoption is given by two variables, the number of heads of households with permanent employment and the district's electrical power. The customers and energy results produced represent for each scenario only the 7% and 9% of the energy demanded, this concentration is shown through thematic maps that allow identifying the districts that have rapid adoption of solar panels. The results are important tools for the planning of the distribution company, the company will have the areas of highest rooftop solar photovoltaic systems penetration to evaluate its distribution system and maintain its reliability levels.

**Keywords** spatial-temporal, logistic growth model, geographically weighted regression, solar potential, solar panel.

**Nomenclature:**

LGM: logistics Growth Model

GWR: Geographically Weighted Regression

DER: Distributed Energy Resource

INEC: Institute National of Statistics and Census

PV: Photovoltaic

RTPV: Rooftop Solar Photovoltaic

## 1. Introduction

In recent years, the fight against climate change has made governments aware of the need to implement different policies that encourage the adoption of renewable energies; for example, some countries base their research on updating their energy matrix with renewable energies [1]. In the same way, Ecuador has proposed its own implementation through decrees, regulations, and projects due to the change in the energy matrix [2]. For instance, the distributed energy resources (DER) income affects the planning of the distribution companies because their plans did not include this type of customer [3]. As a result, it is necessary to evaluate the hosting capacity [3] of the different substations and networks that are part of the system to obtain areas that need repowering due to the rapid adoption.

Within this field, solar panels have gained strength, such as Germany and other countries of the USA that added around 49 GW of photovoltaic capacity in 2019, and Italy with 20GW [5]. While Chile forecasts that in 2050, it forecast can reduce its gas emission at least 70% from renewable energies [6]. Since 2012, the electricity grid change in Spain is notable because the government improved a policy that motivated the implementation of renewable energy. In 2018, Spain had more than 9 GW of capacity in a photovoltaic panel [7]. The change to solar panels is occurring worldwide; as a result, in 2017, the installed capacity was closed to 400GW and it is projected that by 2050 it will be 4500 GW [8].

Facing the reality of the solar panels' growth, it is important to analyse the people's behaviour when they adopt this new technology. The authors mentioned that there are 5 major personality traits applied to 375,00 individuals with 2600 UK zip codes. The results demonstrate that spatial concentrations of people with installed solar panels have produced the tendency to the acquisition of them and more if subsidies are provided by the state [9]. Meanwhile, in the USA, the penetration of solar panels was analysed by applying 3 different behavioural theories: the theory of diffusion to innovation, the value-belief-norm theory, and the corresponding theory of planned behaviour. Based on the results of some studies is possible to identify three different groups: people who have not adopted the technology, the ones who use it to buy novel products tend to install solar panels, and the third ones who tend to use this kind of installation when they see personal benefits in other people [9]. In Germany, a study relates economic factors, socio-demographic and adopted characteristics combined with the effect produced by the neighbourhoods. Through a spatial auto-regression and a spatial model for the error, it is possible to determine that policies with economic incentives are the main conductors of implementation, while taking care of the environment is ambiguous [10]. In the case of the district of Sri Lanka, there was proposed a model based on a negative regression binomial with zero-inflated (ZINBM) aimed to compare the influential factors for the adoption of photovoltaic panels and the adoption factors in developed countries; as a result, the short-term high education and middle-aged people are more apt to adopt photovoltaic panels. Moreover, the medium and long-term policies and the improvement of equipment costs will accelerate the diffusion of this innovation [11].

Different authors have implemented these studies, using different mathematical methods; however, most of them use a linear regression with variations, as in [12] the author employs a logistic model that collected data from neighbourhoods of Woliso, a town in Ethiopia. The results show that healthier places, educated and mainly female houses have a higher preference to technology adoption. A spatio-temporal study was also applied using a logistic growth model (LGM), the temporal component calculates the estimated sections of the city's census that include percentages of people that could acquire solar panels, as well as the analysis of their geographic location [13]. Another model relates the pre-existing installations with their neighbourhoods using a binary logistic model which determined that the influence of the neighbourhood is very positive in the incursion of the technology [14]. Moreover, up-to-date models are used as well as in the case of the Monte Carlo simulation-based penetration estimation, using available GIS tools [15].

The use of solar panels to produce energy has had a quite deep study, this use represents the improvement of its main motivating efficiency. Thanks to studies with different natural oils, it has managed to increase the efficiency of solar panels in hours of maximum radiation [16] and others Other authors have designed algorithms to optimize photovoltaic cells [17]. In base of efficiency studies with the I-V curve, the result shows that the cell made with the correct quantity of thick photoelectrode and dye in ethanol solvent can get a greater efficiency [18] and also, analyses the influence of temperature on the performance of the panels [19]. Other authors analyze the influence of shade, temperature and light [20] on the efficiency of photovoltaic panels, and other authors use fuzzy logic [21] and machine learning to create models that optimize panel efficiency [22]. Therefore, the simulation of energy production based on software must be reliable. To calculate the potential solar energy some authors use PVLIB [23]. The evaluated energy balance intended for photovoltaic modules with PVLIB [24]. The model uses the weather and evaluates thermal behaviour and electrical outputs intended to perform heat flow measurements. Moreover, there is a model that presents the corresponding validation and earlier development of a satellite-based GHI (Global horizontal irradiance) [25]. This model uses different bases to compare the results and concludes that PVLIB information is reliable. Other authors evaluated the accuracy of various irradiance models [26]. They use purchased satellite data of Solar GIS which is comparable with the use of PVLIB data using different models to weather.

To help the integrated planning of distribution companies, the model innovates the methodology by going a step beyond the other models presented. The model is not only a logistic regression of growth, it can also relate the socioeconomic variables obtained in the census to determine the areas that will have greater adoption of the technology in the future. This model is also responsible for evaluating the energy potential in the different areas based on their geographical position. Because of this, the work aims to determine the number and location of potential RTPV customers, so the distribution company can evaluate its system in each of these areas. Therefore, the main contributions that the work presents are:

- A model that allows the determination of the number of RTPV projected for 5 years, considering the current number of customers and the economic capacity of the inhabitants of the area
- A spatial model that adjusts the customer projection spatially, determining the main variables that affect the adoption of the new technology.
- An energy density map that is a function of the solar resource and the number of projected customers divided into census districts.

## 2. Methods

The analysed method consists in a temporal and spatial model that uses different input and output data to calculate the new RTPV systems through three modules: temporal, spatial, and potential. The model was implemented within a GIS platform and programmed with python. The data-oriented is to be entered as a georeferenced map of the city under study with social-economic and technical variables. Fig 1. shows the method screen.

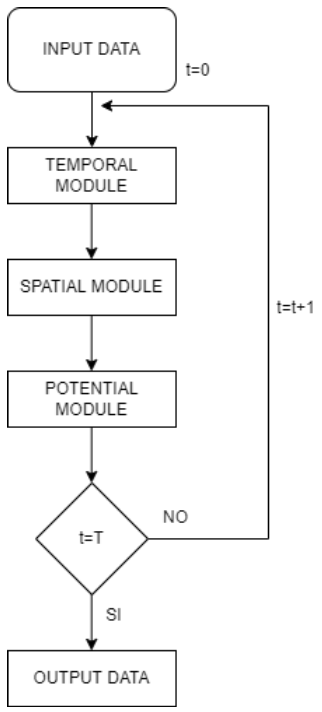


**Fig. 1** Algorithm of the proposed method

### *2.1. Temporal Module*

A model oriented to logistics growth (LGM) was used for the temporal module. The model estimates in each section the increment over time, and the number of residential consumers which is a perspective of solar panel buyers. To do this, the LGM uses the district urban growth model, the population's socio-economic data, and the cost of kWh generated by a solar panel. The temporal module calculates the new end-use of solar panel consumers ( $Y_{s,t,d}^{Obs}$ ) [27] using equation (1).

$$Y_{s,t,d}^{Obs} = \frac{Y_d^*}{1+(\frac{Y_d^*}{Y_{s,0,d}^{Obs}}-1)e^{a_{s,d}t}} \quad (1)$$

Where "s" represents each of the new and current scenarios derived from the adoption of new technologies. Based on the cost of kWh with a solar panel, "t" represents the years spent studying each "s" scenario. Variable "d" represents the different districts of the city. $Y_d^*$ represents in a maximized way the number of households that can acquire this new technology. $Y_{s,0,d}^{Obs}$ is the number of households in which residents can acquire the technology in the year that begins (t=0), $a_{s,d}$ is the indicator that measures each year the increment number of potential users who can acquire the new technology is established by as equation (2).

$$a_{s,d} = a_d^{RC} b_d \frac{BEN_{s,d}}{COS_{s,d}} \quad (2)$$

Where $a_d^{RC}$ represents the level of growth in district d, $b_d$ represents the general interest of the people of the district "d" $COS_{s,d}$ focuses on representing the cost of the kWh with the new technology and $BEN_{s,d}$ represents the cost of a traditional kWh.

When $Y_{s,0,d}^{obs}$ is the updated number of electric stoves that have been installed in the starting year, so it is necessary that $a_{s,d}$ be multiplied by a factor intended to make an adjustment $AF_{s,d}$ which is calculated by an equation (3).

$$AF_{s,d} = \frac{1}{t * a_{s,d}} \ln\left[\frac{Y_{s,t,d}^{His}(Y_d^* - Y_{s,0,d}^{Obs})}{Y_{s,0,d}^{His}(Y_d^* - Y_{s,t,d}^{Obs})}\right] \quad (3)$$

Where $Y_{s,t,d}^{His}$ represents the historical records of the adoption of the new technology, the same that was collected from the conditions of the different scenarios "s" in the year "t".

### *2.2. Spatial Module*

It was used through geographically weighted regression (GWR) to the spatial module, GWR uses the spatial interactions to adjust the LGM results using socioeconomic data to obtain the number of consumers who will be prospective buyers. This is described by Eq. 4 [28]

$$Y_{s.t,d} = \beta^1_{s,t,d} X^1_d + \beta^2_{s,t,d} X^2_d + \dots + \beta^k_{s,t,d} X^k_d + \varepsilon \quad (4)$$

$Y_{s.t,d}$ is the prospective buyers of new technology, $x^k_d$ represents a set of properties of the inhabitants in the social and economic sphere $\varepsilon_{s,t,d}$ is the difference between $Y_{s.t,d}$ and $Y^{Obs}_{s,t,d}$, $\beta^k_{s,t,d}$ is a sensitivity measure associated with each social and economic characteristic $X^k_d$, $\beta^k_{s,t,d}$ are calculated as equation (5).

$$\beta^k_{s,t,d} = (X^{k'}_d W_d X^k_d)^{-1} X^{k'}_d W_d Y^{Obs}_{s,t,d} \quad (5)$$

Where $W_d$ is a matrix in the form of a square, which is shown below [27]:

$$W_d = \begin{bmatrix} W_{d,1} & 0 & \dots & 0 \\ 0 & W_{d,2} & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & W_{d,j} \end{bmatrix} \quad (6)$$

The data in the diagonal $W_{d,j}$ relate spatial weights proximity to the district “d” with multiple census tracts in the city. The Gaussian estimation tool is used to calculate these values this tool is available in ArcGIS.

### *2.3. Potential solar module*

The potential module needs to calculate the radiation in the different study zones, for this reason, it is necessary the variables like time (day and hour), position information (latitude and longitude), radiation from the global horizontal plane, and mounting information (inclination and azimuth angles of inclined plane), albedo and shading [29].

PVLIB is an open-source code that can help with the calculation of radiation facilitated by Sandia Laboratories [29]. The code uses the modeled in [30] represented by equation (7).

$$C_{module} \frac{dT_{PV}}{dt} = L^*_{PV} + SW_{tot} - Q_{H\_PV} - P_{out} \quad (7)$$

Where $C_{module}$ is the projected heat capacity $(JK^{-1})$ of the module $T_{PV}$, is the temperature of the module (K), $L^*_{PV}$ is the longwave radiation of the PV, $SW_{tot}$ the total radiation $(Wm^{-2})$, the sensible heat flux $(Wm^{-2})$, and the open source that can $P_{out}$ the electrical power, which is produced by the panel $(Wm^{-2})$. This approach implies that the average temperature of the module space is calculated.

PVLIB follows 5 steps to obtain the potential of the zone with a specific panel, these steps are shown in Fig 2.

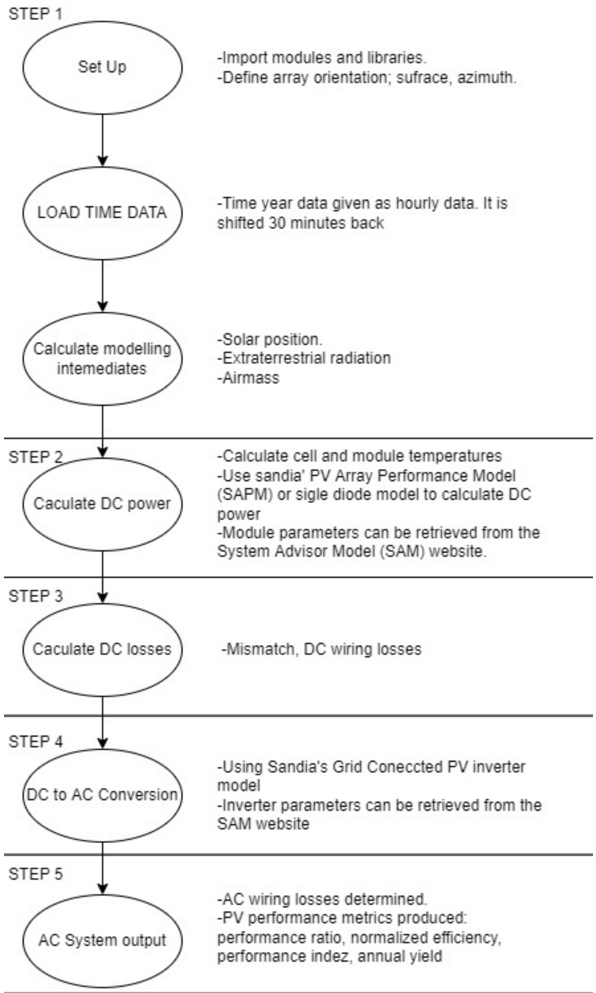


**Fig 1.** PVLIB workflow chart.

## 3. Application of the proposed method

The method was applied in Cuenca, it is an Ecuadorian city. Cuenca is considered one of the most important cities in the country and with the largest population, it has 670,000 inhabitants. CENTROSUR is the company of electrical distribution.

CENTROSUR provides electricity to 403,776 customers, which 356,727 are residential, while the rest are commercial, industrial, and others. The study is focused on an Urban Cuenca zone that has an area of 70.6 km2, 152.057 consumers, and represents 56% of CENTROSUR's total demand.

The method was applied only to resident consumers in the Urban area of this place. Cuenca has a policy to conserve historic areas [32], this policy restricted the implementation of solar panels on the rooftops inside the “Historic Centre”.

Ecuadorian government implemented a policy named “Regulatory framework for Distributed Generation for self-supply of regulated electricity consumers ” [33] that allows to installation max 1 MW of distributed generation.

The consumers of this technology are known as Rooftop Solar Photovoltaic (RTPV). These consumers have two options to apply: Net Billing or Net Metering, which allow them to deliver or consume energy. In the case of consumption, the distribution company does not pay that value of energy but accumulates a value that could be used for the following months.

This work takes as reference the division of the city of Cuenca from the population census to determine the number of dwellings, in which citizens can be potential buyers for an estimated time of five years, and socio-economic census data provided by the Institute National of Statistics and Census (INEC). The parameters of each one of the modules are determined in sections 3.1-3.3.

*3.1. Temporal Module*

The adoption of RTPV in Cuenca had an important growth in the last year. Cuenca has 16 RTPV consumers and only 5 are resident RTPV consumers. For this reason, the adoption of induction stoves will help to calibrate the adoption of RTPV $Y_{s,t,d}^{Obs}$.

$Y_s^*$ is the maximum number of dwellings in which citizens can acquire RTPV, this value was calculated with stratification of INEC that consists of classifying the homes into 5 categories with different economic possibilities. This shows that only homes with category A or B can purchase the technology [34].

The value of $a_{s,d}$ is calculated using equation (2), where $a_d^{RC}$ represents the level of growth of customers who purchased induction cookers in the sector "d" of the years 2018-2021; $COS_{s,d}$ represents the cost of energy generated through solar panels, $BEN_{s,d}$ represents the value of the energy of electric distribution company. $b_d$ is calculated through a study of stratification INEC to obtain the market potential of RTPV. The $a_{s,d}$ was adjusted by using equation (3) and the proper historical record adoptions of electrical stoves.

*3.1.1. Economic Scenarios*

The method proposes two scenarios, S1 is when the value of the energy with panel solar is higher than the traditional energy, this scenario is very common in Ecuador because the price of kWh with panel solar is around \$0,13-0,15 [35], but this price is fluctuating because this depends on the size of the installation, while the tariff of kWh in Ecuador is \$0,10. That is to say when $COS_{s,d} > BEN_{s,d}$.

Scenario S2 is when the cost of kWh with the solar panel is less than traditional kWh. This scenario pretends to simulate the behaviour of Latin-American [36] countries with high solar panel adoptions [37] and Chile [38] that is when $COS_{s,d} < BEN_{s,d}$. As a result, it simulates when the power generation with solar panels is less than the conventional kwh.

*3.2. Spatial Module*

The results of the census, which was conducted in 2010, as the source of social and economic data, which were used to determine the RTPV. The socio-economic variables with the best R2 were selected for the study. These variables are:

$X_d^1$: Number of households in which the head of household has a permanent job.

$X_d^2$: Number of dwellings in which their owners reside.

$X_d^3$: Electric power provided in district d;

$X_d^4$: Residences in which there are more than five inhabitants and at least one is a permanent resident.

$X_d^5$: The educational level of the head of the household.

*3.3. Potential Solar Module*

To evaluate the potential solar module the panel CHSM72M-HC Series 450 W of the company Astro energy was selected. Currently, in Ecuador, different companies install this type of panel because it is the most marketable.

The policy described in Ecuador allows the consumer to install a maximum value of kWp with a solar panel that does not exceed the annual consumption average. For this reason, existing RTPV residential consumers in Cuenca have a power average of 3.64 kWp and this power value has been analysed in distribution systems. This power will be the maximum of kWp to analyse the potential energy [39].

## 4. Results and discussion

The module spatial metrics in Table 1 show, that the best characterization of the model is for scenario 1 with an R2 de 0.32 and sigma 3.91. Based on the results, both scenarios scenario 1 and scenario 2 are the most influential variables in the adoption of a solar panel.

**Table 1.** Metrics of GWR in both scenarios.

| Metric | S1 | S2 |
|---|---|---|
| R2 | 0.32 | 0.28 |
| Sigma | 3.91 | 3.11 |

Table 2 summarizes the annual growth of RTPV consumers in the study zone defined for the two adopted scenarios. Table 1 shows that 2.57% of consumers in scenario 1 will be converted into RTPV consumers while in scenario 2 the 3.79% of consumers will convert into RTPV consumers.

**Table 2.** Annual results of consumers in which the residents are prospective adopters.

| Year | S1 | S2 | Growth S1 | Growth S2 |
|---|---|---|---|---|
| First | 1263 | 1103 | 1.15% | 1.01% |
| Second | 1681 | 1241 | 1.54% | 1.13% |
| Third | 2039 | 1433 | 1.86% | 1.31% |
| Fourth | 2315 | 1630 | 2.11% | 1.49% |
| Fifth | 2817 | 4147 | 2.57% | 3.79% |

Fig 3. Shows the spatial distribution of RTPV consumers. The spatial module estimates 2.818 consumers for scenario 1 and 4147 for scenario 2, Fig 4. shows consumers' spatiality distributed. The results demonstrate that now the cost of kWh with solar panels is higher than the traditional system and for this reason, the adoption is the lowest. While the result of scenario two shows that if the cost of kWh with solar panels were lower than a traditional kWh, the adoption would be faster.

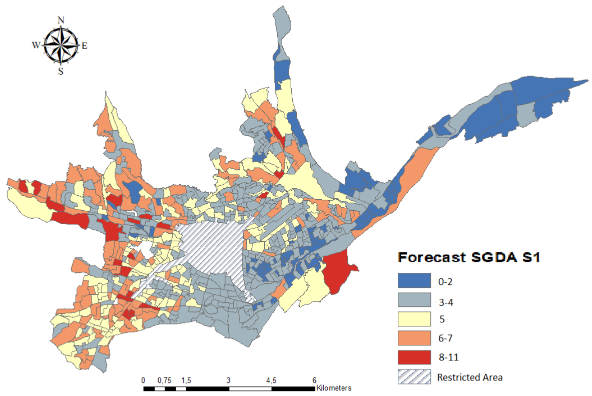


**Fig 2.** Spatial distributions of RTPV consumers for the last estimated year of scenario 1.

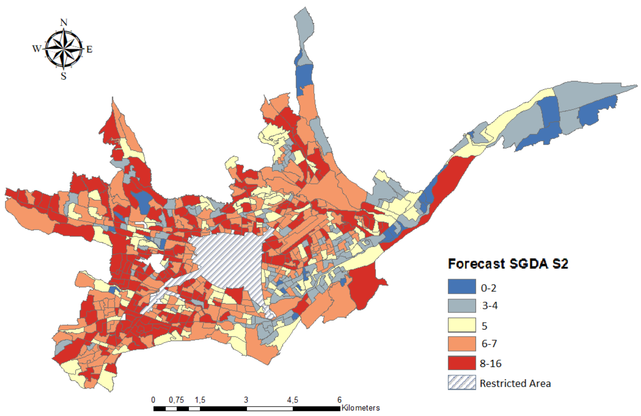


**Fig 3.** Spatial distributions of RTPV consumers for the last estimated year of scenario 2.

With the forecast of RTPV systems, the potential module will be calculated, the energy produced with solar panels is 3.64 kWp, so the energy average is 390 kWh monthly. This value depends on the georeferenced position of the zone of study. To obtain the total energy is necessary to multiply the number of RTPV consumers in each zone by the energy calculated.

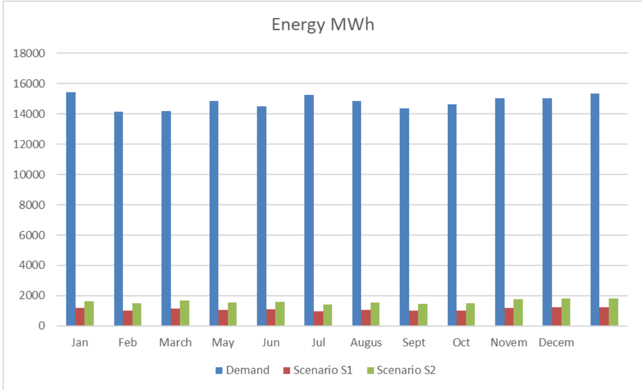


**Fig 4.** Energy monthly produced by two scenarios.

The demand for energy for residential consumers in 2021 registered by CENTROSUR was 161,397 GWh, CENTROSUR considering an annual growth rate approximately of 2% Fig 5. Shows the relation between the energy produced by RTPV and the demand unto 2026.

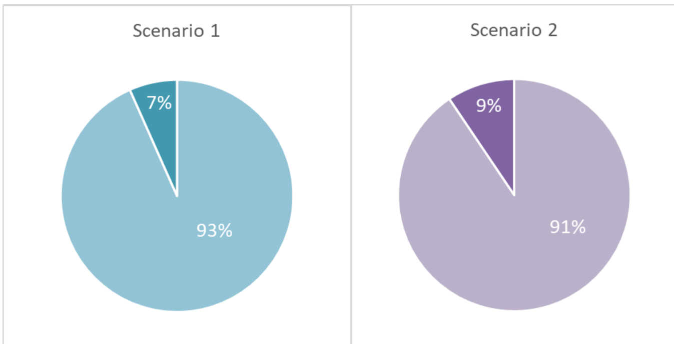


**Fig 5.** Percentage of energy in which apport of RTPV consumers.

Fig 6. projects the level of energy new RTPV customers would contribute to CENTROSUR's energy demand in 2026. Scenario 1 shows that new users can cover up to 7% of the estimated total demand, while scenario 2, with more customers, could cover up to 9% of the demand. This additional 2% difference provided by scenario 2 could help the energy matrix of the utility company.

The distribution of consumers provided by the spatial module has a direct relation with the energy produced by RTPV consumers, Fig 7 and Fig 8 show the energy produced spatially for both scenarios.

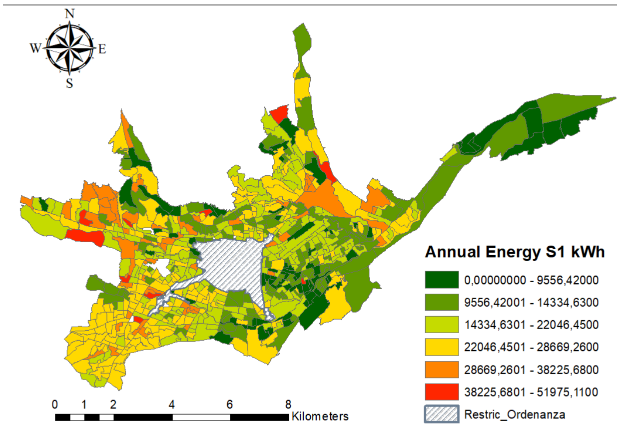


**Fig 6.** The energy that was produced by consumers RTPV in scenario S1.

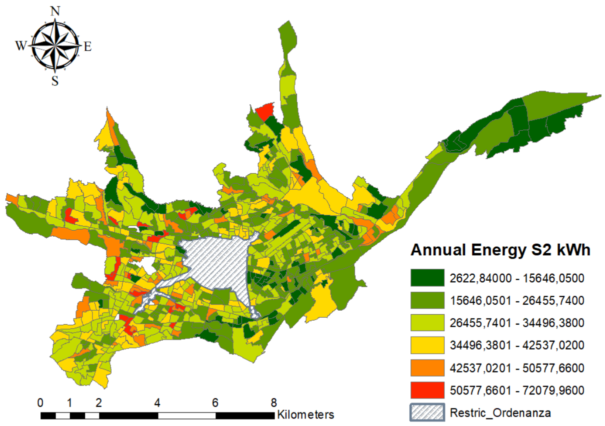


**Fig 7.** The energy that was produced by consumers RTPV in scenario S2.

## 5. Conclusion

In this study, the main variables to improve the people's decision to adopt solar panels technology were the number of dwellings in which the head of household has a permanent job, in addition to installed electricity, due to the current value of the implementation of the already mentioned technology is not accessible for all consumers.

Inside Ecuador, Cuenca city has a privileged location in terms of radiation: however, the economic condition in this city does not allow a higher adoption, the best scenario (S2) represents only the 3.8% of consumers of CENTROSUR, it is expected that this type of technology will be obtained in a medium term of 5 years.

The value of energy produced by RTPV consumers is low, it approximately represents only 8% of the consumption of energy. However, it is necessary to analyse these values with the existing grid in terms of power flow because the grid has different thermal and electrical limits. For the location of the city, it can be easily covered a high percentage of the consumption of energy with solar panels, but with the electrical system is impossible because this one will not support the bidirectional flow. However, isolated systems could be installed to avoid overflows and instability in CENTROSUR's distribution system, as it has been doing in its Amazonian project "Yantsa li Etsari", although for the moment the regulation does not allow it in the city.

The results show that it is necessary to implement a regulation that encourages consumers to implement the use of solar panels, as they show that the projected increase is not enough to cover up to 20% of the total energy demand since a total of 11,000 additional panels should be incorporated to the projected ones.

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