ANALYSIS OF THE INSTALLATION OF PHOTOVOLTAIC SYSTEMS IN DENSELY URBAN CENTERS FOR THE FORMATION OF ENERGY COMMUNITIES: A CASE STUDY IN THE METROPOLITAN REGION OF SÃO PAULO, BRAZIL

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ABSTRACT

In response to climate concerns, promoting renewable sources such as photovoltaic systems (PV) in urban areas is crucial. However, the shortage of rooftop space in densely populated urban centers makes installations difficult. Consumers can form energy communities (ECs) to address this issue and obtain collective PV benefits. This paper presents a case study that uses a geographic information system (GIS) to identify the most suitable areas for PV installation within groups of consumers forming ECs in vertically growing urban areas. The methodology consists of two modules using GIS data and sustainable development agency databases. First, suitable installation areas within an Energy Community (EC) are identified. Secondly, the impact of each PV in each ECs on the electrical distribution network (EDN) is assessed. This approach is applied to the densely urbanized city of São Paulo. The results show that when establishing ECs, the technical losses (TLs) in the system decrease. This reduction could have a positive impact, reducing of costs and enabling tariff differentiation for each ECs and added value to the sustainable development of the city.

Keywords: Energy Communities, Distribution System, Photovoltaic System, Electrical Technical losses.

1 Introduction

In recent years, there has been a notable increase in the incorporation of distributed energy resources (DER) into the electrical distribution network (EDN) [1]. These resources include distributed generation, energy storage, electric vehicles, charging infrastructure, energy efficiency strategies, and demand management [2]. The growth in DER integration can be attributed to decreasing investment costs, advancements in telecommunications and control technologies, and greater consumer involvement in the EDN. Projections indicate that by 2050, around 83% of consumers will assume a more active role, transitioning into prosumers [3].

On the other hand, the construction boom in the new century promoted the accelerated growth of vertical structures, mainly in densely populated cities [4]. This type of infrastructure can bring significant challenges for residents when installing photovoltaic systems (PV) due to limited space on their rooftops and shading issues, among other factors [5]. Thus, the creation of strategies and incentive policies for consumers located in urban cities becomes crucial, enabling the development of sustainable cities [6]. In this context, a recent alternative to address these issues is the establishment of energy communities (ECs) [7]. These ECs are legal entities formed by a collective of members who voluntarily and cooperatively establish their objectives to achieve energy, social, environmental, and economic benefits [7]. In relation to PV, ECs allow the optimization of these resources [6], guaranteeing the correct operation of the EDN, and reducing technical losses (TLs) of the distribution system, due to the proximity between the generation and consumption points [2].

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Some papers recently published in high-impact international journals related to creating ECs and evaluating TLs are presented below. In [1], the authors assessed different scenarios to determine active TLs based on the location and sizing of PV generation. In [8], the authors proposed a methodology that allows relating the percentage of PV generation penetration in terms of TLs. The authors assessed the impact of clustering PV generation through time series analysis. On the other hand, in [6], the authors proposed a stochastic methodology based on Monte Carlo simulations to assess the impact of creating ECs on the EDN. These authors observed that promoting the aggregation of loads and generators is a crucial factor in optimizing EDN operation. In [9], the authors compared TLs in the EDN, considering the presence of individual PV generation productors and the clustering of consumers in ECs. They found that ECs could decrease TLs in the EDN.

However, a common limitation of these studies is the omission of vertical urban growth in densely populated areas when establishing ECs, which can alter the PV installation rate due to limited rooftop space in metropolitan cities. Thus, unlike the previously mentioned works, this paper proposes a methodology that leverages a geographic information system (GIS) to identify the most suitable areas for PV installation within a group of consumers forming an EC. Additionally, the influence of the previously identified PV system penetration within the EDN for each established EC is analyzed. Moreover, a case study is proposed to evaluate a EDN located in the metropolitan region of São Paulo, Brazil. The results of this work may bring the attention of electric distribution companies, consumers, and public entities advocating for sustainable urban development about the benefits of establishing ECs within metropolitan cities. It is important to mention that economic analysis is not part of the objectives of this work.

2 Performed Methodology

The methodology comprises two modules shown in Fig. 1. These modules help identify the impact an EC causes in the EDN in urban areas with vertical growth, considering the formation of ECs composed of the group of benefiting consumers and minimizing TLs in the EDN.

In the first module, the rooftops not affected by shading are identified, and with the aid of QGIS software [10], the area value of these rooftops is estimated. Simultaneously, the EDN of the study area is modeled using OpenDSS software for EDN simulation [11] and QGIS, providing the spatial location of each component of the electrical EDN. With this information about the rooftop areas and the EDN, consumer clusters are created, referred to as ECs. The total area value available for each consumer cluster, the study area's irradiance, the PV panel's efficiency, and the PV generation potential for each of these ECs are determined.

In Module 2, the PV generation potential values for each group of rooftops, which were estimated in Module 1, were used. These values were associated with existing data from four distinct characteristic curves derived from real measurements of a study conducted for a neighboring district of the study area. Using Python and OpenDss, simulations were carried out to analyze the impact of PV of each EC to identify which group contributes most significantly to reducing the TLs in the EDN.

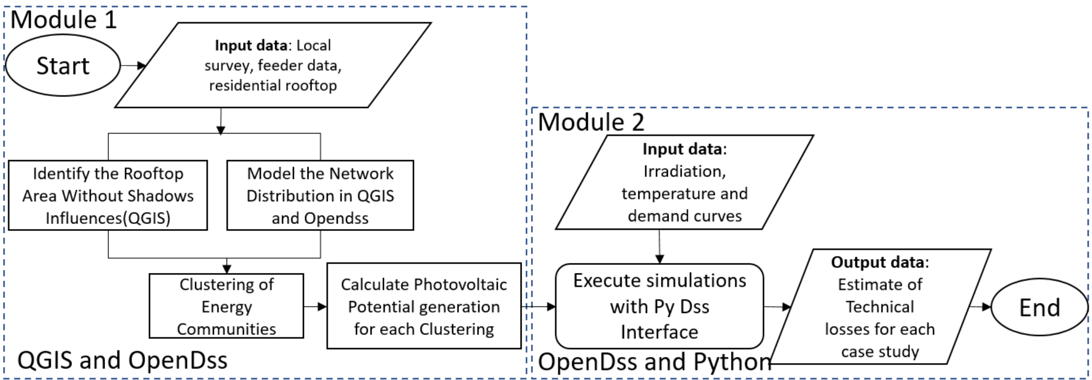

Figure 1: Flowchart of the Proposed Methodology

3 Results and Discussion

The input data used in the case study are defined in this section, including the characteristics of the EDN, the scenarios considered for applying the performed methodology, the characteristics of PV generation, and finally, the results obtained.

A. Input Data

a) Study Case

For the choice of ECs, the Jardim Santo Alberto neighborhood, located in the city of Santo André, state of São Paulo in Brazil, was used due to its characteristics, such as vertical growth, adoption of PV, and proximity to businesses, which made it an attractive option. Similarly, an unbalanced medium voltage EDN was used to evaluate the impact in TLs, from the openly available ANEEL database was used [12]. The EDN used in the study case comprises 126 lines, 127 nodes, 99 transformers and 172 loads, as shown in Fig. 2. Likewise, considered is the available area of the rooftops of each EC seen in Fig. 3. Due to data privacy concerns, loads were assessed based on the transformer's maximum capacity, and unbalanced loads were considered with a the demand curve taken into account is depicted in Fig. 4.

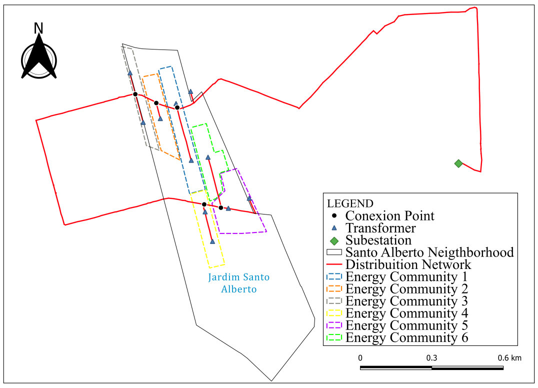

Figure 2: Location of the Study Case

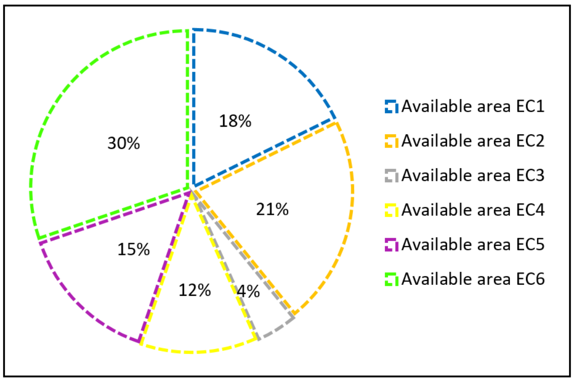

Figure 3: Avalible Areas for Energy Community

b) Characteristics of Photovoltaic Generation

The group of ECs was limited to be linked to transformers with a minimum nominal power of 75 kVA due to the grouping of prosumer units. In addition, to broaden the observability and data analysis, typical irradiance, temperature, and demand curves obtained from a project carried out in the same location were considered [5]. These curves correspond to different types of days: sunny, partly sunny, partly cloudy, and cloudy, as shown in Fig. 4. This selection of curves will allow us better to understand the impact variability in the proposed scenarios.

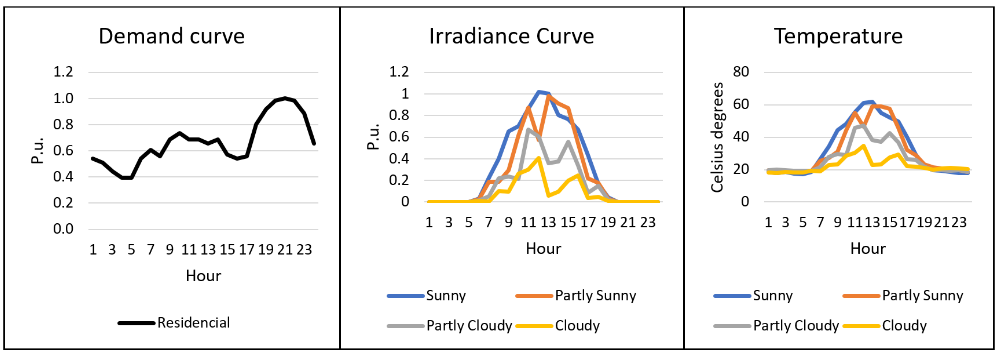

Figure 4: Demand, Irradiance, and Temperature Curves

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c) Proposed Simulation Scenarios

For the case study six scenarios are proposed from the identification and grouping of the utilization of available areas on the rooftops for the installation of PV and the formation of ECs. The remaining six scenarios are based on individual simulations of each EC, allowing researchers to examine how different adoption and development levels affect EDN. The possibility for parallel or cooperative interactions across ECs to maximize group advantages and energy resilience is not covered in the paper.

B. Results

This section presents the results obtained from the application of the case study methodology are presented below. To streamline the extraction of results, the Py DSS Interface library was used. The main goal was to identify the areas within the ECs that could contribute most significantly to reducing TLs in the EDN and alleviating congestion.

As shown in Table 1, the results in terms of reducing TLs vary considerably, ranging from 0.4% for a cloudy day to a maximum of 7.54% for a sunny day. But these findings do not suggest that the best option and application are within the sixth scenario. Because, if we look at it from a performance perspective, which is determined by comparing the area used for PV installation to the amount of TLs it manages to reduce, the scenario that demonstrates the highest performance is the third scenario, which only utilizes 4% of the rooftop area, achieving up to efficiency of 32%, compared to the modest performance of the sixth scenario that uses more than 30% of the rooftop area and as a maximum reaches 8% of performance, as shown in Fig. 3 and Table 1. These results indicate that extensive areas in urban zones are not necessary to promote the participation of ECs and encourage self-consumption, as well as sustainable urban development. However, the observed variability in the levels of TLs reduction among each EC, coupled with research constraints such as the challenge in characterizing real consumer loads due to data privacy concerns, as well as the complexity associated with modeling the behavior of the EDN, underscores the importance of ongoing exploration of these issues. This approach is crucial to ensure an equitable distribution of benefits among those contributing to the urban sustainable development.

Scenarios	Sunny		Partly Sunny		Partly Cloudy		Cloudy		Performance	
	TLs Reduction		TLs Reduction		TLs Reduction		TLs Reduction		Cloudy	Sunny
	[kW]	[%]	[kW]	[%]	[kW]	[%]	[kW]	[%]	[%]	[%]
Scenario 1	52.31	2.01	43.78	1.68	26.039	1.00	10.38	0.40	0.7	3.4
Scenario 2	104.82	4.03	87.87	3.38	52.584	2.02	20.41	0.78	1.1	5.7
Scenario 3	114.61	4.40	96.01	3.69	57.296	2.20	21.86	0.84	6.1	32.1
Scenario 4	128.72	4.95	107.79	4.14	64.23	2.47	24.16	0.93	2.4	12.5
Scenario 5	158.86	6.10	132.95	5.11	79.02	3.04	28.99	1.11	2.3	12.6
Scenario 6	196.13	7.54	164.46	6.32	98.50	3.79	36.50	1.40	1.4	7.5

Table 1: Reduction of Technical losses

The focus on ECs and the results obtained create opportunities for a more comprehensive analysis, emphasizing the need to address future work by considering, various geographical spaces, using technology supported by computational intelligence for maximum profit, regarding the selection of PV installation areas, as well as the incorporation of a broader array of REDs, delving into the management and optimization of the benefits for each ECs. Furthermore, conducting economic and regulatory analyses for this new market participant to explore specific electricity tariffs for ECs and associated remuneration frameworks. This need could give rise to possible conflicts and regulatory gaps that would harm the development of ECs. As the autor [3] also emphasizes the need of managing DERs in metropolitan areas, because poor management can increase electricity costs and exacerbate social inequality.

4 Conclusions

This study employs an innovative approach to address the current energy and sustainable development challenges. Through the methodology used, it has been demonstrated how ECs can play a vital role in the transformation of urban electric networks into more resilient and sustainable models.

Analysis of the interactions between the integration of PV within ECs and the existing distribution infrastructure has revealed a significant reduction in the load on the network and, consequently, a decrease in TLs. This enhances the efficiency of the electrical system and opens avenues for evaluating novel pricing structures and consumer advantages. The ECs strategically placed in densely populated urban areas, along with government laws and incentives, highlight the significance of an integrated strategy involving numerous stakeholders. For the shift towards a more sustainable energy model to be effective, cooperation between local government agencies, businesses, communities and researchers is essential. Future research might build on the results of this study by investigating generation and consumption optimization within ECs and using the method in various geographic and regulatory contexts.

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