Seeking a possible Positive Energy Districts (PEDs) location choice from a local context, a case study in Tainan City, Taiwan

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Abstract (up to 125 words)

COP28 emphasized the urgent need to accelerate energy transitions and decarbonization. As major centers of energy consumption and carbon emissions, cities have become critical arenas for implementing these transitions. The EU and IEA have actively promoted Positive Energy Districts, shifting the focus from individual buildings to the district scale to enhance energy efficiency. This study focuses on socioeconomic indicators and explores key indicators influencing residential electricity consumption (REC). Using Tainan City as a case study, it combines rooftop PV generation potential and REC forecasting to evaluate the energy self-sufficiency rate of each district. The results indicate that only “household income” shows a significant positive correlation. Future research could adopt more detailed level data to improve assessment accuracy and provide evidence-based support for urban energy planning.

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6) released in 2023 projected that global temperatures are likely to rise by 1.5°C within the next two decades. This increase is expected to intensify climate-related hazards and may further exacerbate challenges related to energy, water resources, and food security. In response, the 28th Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change (UNFCCC) emphasized the need for all countries to enhance their Nationally Determined Contributions (NDCs), improve energy efficiency, and adopt new technologies to advance energy transition and decarbonization efforts. Over 100 countries have now declared net-zero emissions targets, including Taiwan, which has committed to achieving net-zero emissions by 2050. Taiwan’s 2050 Net-Zero Emissions Roadmap outlines four major strategies: energy transition, industrial transformation, lifestyle change, and social transition.

According to the International Energy Agency (IEA), cities account for approximately 75% of global energy consumption and 70% of global greenhouse gas emissions. In this context, **cities—being densely populated areas with high energy demands and concentrated carbon emissions—have emerged as critical arenas for driving energy transitions and realizing net-zero goals**. Consequently, institutions such as the European Union and the IEA have initiated a range of urban-centered energy transition policies and pilot programs. These efforts have evolved from single-building scale initiatives such as near-zero energy buildings (NZEBs) to larger, district-scale approaches exemplified by Positive Energy Districts (PEDs). The European Union, under the Strategic Energy Technology Plan (SET-Plan), has set a goal of establishing at least “100 PEDs” across Europe by 2025. Simultaneously, IEA Annex 83 has been conducting research into the definitions, implementation methods, tools, and technologies associated with PEDs. Projects like MAKING-CITY have also provided detailed methodologies and procedures for evaluating PEDs, emphasizing that such evaluations must consider not only urban form and energy infrastructure but also the social structures of the target districts.

Nevertheless, most existing studies on PEDs have focused on location suitability assessments based on comprehensive, objective indicators, aimed at aiding policymakers in the strategic deployment of PEDs. While these evaluations help identify areas with higher potential for PED implementation, **the Urban Agenda for the EU underscores the critical role of public participation in energy transitions**. Given the diverse socioeconomic conditions across regions, variations in energy use behaviors and public acceptance may significantly influence the feasibility and effectiveness of PED implementation. However, current studies seldom address the potential influence of "local resident characteristics"—such as economic status and demographic composition.

This study proposes the following research objectives:

1. To explore the key factors influencing residential energy consumption from a "socioeconomic perspective", with a particular emphasis on how resident structures affect energy behavior. This aims to address the current research gap in PEDs evaluation, which often overlooks the role of residents.
2. To conduct an empirical study in a selected city in Taiwan, integrating energy demand forecasting and potential analysis to evaluate the "energy self-sufficiency rate" of each administrative district. The study further assesses the feasibility and limitations of these districts as potential PEDs units.

2 LITERATURE REVIEW

2.1 Positive Energy Districts (PEDs)

2.1.1 Definition of PEDs

According to the European Commission, a Positive Energy Districts is defined as "a set of buildings where the community controls the energy flows and aims at a net positive energy balance over a year by utilizing renewable energy sources". Meanwhile, the SET-Plan defines PEDs as "energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy." Based on these definitions, **PEDs refer to a geographically connected cluster of buildings with internal energy exchanges that aim to achieve a net-positive energy status through efficient and flexible use of renewable energy sources.**

The European Energy Research Alliance (EERA) further categorizes PEDs into three types based on differences in geographic boundaries and energy balancing approaches: **PED autonomous**, **PED dynamic**, and **PED virtual**. PED autonomous has clearly defined geographic boundaries and achieves complete energy self-sufficiency within the district, allowing energy export but prohibiting external energy input; PED dynamic, by contrast, allows energy exchange with other PED systems; PED virtual enables energy production and storage systems to be located outside the district while still serving energy needs within the area.

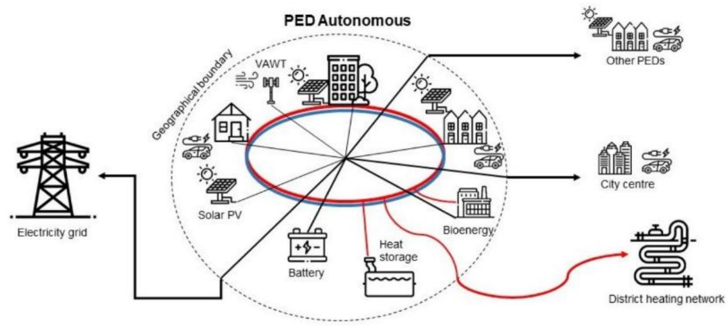

Figure 1. PED autonomous diagram

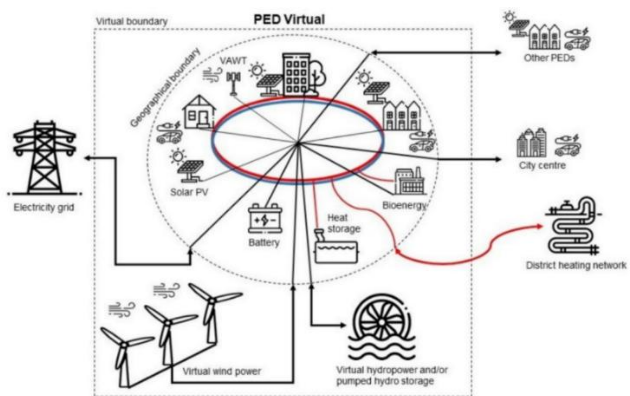

Figure 2. PED virtual diagram

2.1.2 Benefits and Challenges of PEDs

According to the *Positive Energy Districts Solution Booklet*, compared to achieving zero or positive energy targets at the individual building level, the diverse usage patterns of different building types often make it difficult to meet these goals in isolation or may result in energy overproduction and waste. Therefore, shifting the focus to district- or community-level PEDs enables more flexible and efficient energy utilization.

However, the current definition of PEDs still lacks clarity, particularly in terms of geographic boundaries, which can vary significantly depending on local characteristics. This implies that there may not be a one-size-fits-all PED model applicable across different contexts, and location-specific considerations are necessary during site evaluation. Furthermore, the need to account for “end-users” and adopt an “area-based” policy approach tailored to local characteristics, particularly in fiscal and social dimensions. It also criticisms the idealistic nature of PED autonomous models, which often overlook challenges such as high population density, limited space, and constrained access to renewable energy sources in urban areas. Hence, the development of “dynamic and virtual” PEDs in conjunction with Virtual Power Plants (VPPs) is viewed as a more viable pathway.

2.1.3 Methods for Evaluating PED Locations

Two uncertainties complicate the definition and planning of PEDs. First is the **geographic boundaries issue**—the appropriate size and boundaries of PEDs may vary depending on city-specific characteristics, affecting the feasibility of renewable energy deployment and energy consumption levels. Second is the **parameter selection issue**—the suitability of PED locations depends on multiple factors across technological, social, economic, and environmental domains, each with a wide range of potential indicators. Therefore, identifying appropriate evaluation indicators is critical for PEDs planning.

Current methods for identifying promising PEDs locations often use Geographic Information System (GIS)-based overlay analysis. Given the multidimensional nature of the relevant indicators, many studies adopt Multi-Criteria Decision-Making (MCDM) or Multi-Criteria Decision Analysis (MCDA) approaches, combining expert judgment to determine key indicators and weights, followed by quantification and statistical analysis across candidate areas.

2.1.4 Why Taiwan's Urban Context is Suitable for PEDs

Taiwan is heavily reliant on energy imports, and most power plants are located far from the areas where energy is actually consumed. This spatial separation between energy generation and usage leads to greater energy transmission losses and, consequently, energy waste. **Given Taiwan's high degree of urbanization and population density, urban areas present a promising opportunity for implementing PEDs that flexibly utilize energy at a district scale.** Additionally, Taiwan faces land scarcity, and the siting of renewable energy facilities often leads to land-use conflicts, particularly with agricultural lands—an issue that has drawn strong opposition from environmental groups. Strategically deploying renewable energy in suitable urban areas and efficiently managing its distribution could help alleviate pressure on valuable farmland while preserving food security.

Among Taiwan's cities, **Tainan stands out as one of the regions with the highest installed capacity of solar photovoltaic systems**, and it has high solar energy potential. The local government has also taken proactive measures to promote urban decarbonization, including the development of Taiwan's first low-carbon community. However, most solar panel installations currently adopt ground-mounted systems located in rural areas, distant from urban centers where energy demand is greatest. This spatial mismatch has raised concerns related to land use and environmental justice. Consequently, this study selects Tainan City as a case area to evaluate potential PED locations. By integrating GIS spatial analysis and renewable energy potential assessments, this research explores the feasibility of implementing renewable energy systems in urban settings and aims to provide insights for future PED planning and policymaking in Taiwan.

2.2 Socioeconomic Indicators Influencing Residential Electricity Consumption

Residential electricity consumption (REC) is closely related to household characteristics. Identifying key factors that significantly influence residential electricity use can contribute to reducing consumption and can also be used to forecast future electricity demand.

Zhifeng et al. (2018) reviewed previous studies on the psychosocial factors influencing residential electricity behavior. Commonly cited indicators include: **household size**, **children**, **age of household**, **education level**, **social status**, **household income**, and **housing type**. These indicators can have either positive (i.e., increasing) or negative (i.e., decreasing) effects on electricity use. However, results vary by region—indicating that the same indicator may show different effects depending on the local context. This suggests that each country or region should identify its own influential indicators and explore the underlying reasons behind these differences.

Najeeb et al. (2024) conducted a systematic review of determinants of residential electricity consumption in South Asia, East Asia, and Southeast Asia, covering socioeconomic, building-related, locational, and environmental-climatic dimensions. In the socioeconomic domain, several frequently studied indicators were identified. The review showed that household income, household expenditure, household size, age of the head of household, and educational attainment of the head of household are significantly correlated with electricity consumption. Meanwhile, indicators such as household size, age of the head, number of children, social class, household occupation, and unit electricity price were found to have either a weak or no statistically significant effect in some contexts.

In addition, within the context of urban energy transition, public perception, acceptance, and willingness to adopt renewable energy are critical social factors. Stakeholders may exhibit different attitudes toward renewable energy depending on their roles and interests. Masoud et al. (2015) found that the acceptance and willingness to use renewable energy are positively influenced by moral norms, attitudes, and perceived behavioral control (PBC). These factors can be useful for predicting the regional willingness to adopt renewable energy technologies.

Figure 3. Socioeconomic Indicators of REC

Indicators	Studies	Effect
Household size	• Yohanis et al. (2008) found that in Northern Ireland, apartments housing four or more individuals exhibited the highest annual average electricity consumption. • Bartiaux 和 Gram-Hanssen (2005) concluded that among various household characteristics, the number of household members had the most significant correlation with electricity use.	＋
Children	• Mcloughlin et al. (2012) demonstrated that households with children tend to consume more electricity than those without. • Bartiaux 和 Gram-Hanssen (2005) found a contrasting result, reporting that households with two or more young children (aged 0~9) showed reduced electricity consumption, suggesting that behavioral patterns associated with childcare may influence energy use differently.	＋/－
Age of household	• Yohanis et al. (2008) observed that households with members aged between 50 and 65 had relatively higher electricity consumption compared to other age groups. • Leahy 和 Lyons (2010) found that households where members were primarily aged 45~64 consumed more electricity than those aged 35~44, while consumption decreased significantly in households where members were over 64 years old.	＋/－
Education level	• Bartiaux 和 Gram-Hanssen (2005) indicated that higher educational levels were associated with lower household electricity consumption.	－

Indicators	Studies	Effect
	• Cramer et al. (1985) found no significant correlation between education level and electricity consumption in the United States and the Netherlands.	
Social status	• Mcloughlin et al. (2012) reported a positive relationship between socioeconomic status and electricity consumption, suggesting that higher-income households tend to consume more energy. • Leahy 和 Lyons (2010) noted that the economic situation of household members did not significantly affect electricity demand.	+
Household income	• Yohanis et al. (2008) found that households with higher annual incomes in Northern Ireland had higher levels of electricity use.	+

3 METHODOLOGY

3.1 Introduction to the Case Study Area

The empirical case study focuses on the former urban area of Tainan City, encompassing six administrative districts: East District, South District, North District, Annan District, Anping District, and West Central District. The total area of the study region is approximately 176.3 km², with Annan District accounting for the largest share at 60.8% of the total area. As of the end of 2024, the total population of the study area is approximately 779,000, with Annan District having the largest population at approximately 203,000. The average population density of the area is around 4,419 persons/km². In terms of building characteristics, the average building age in the area is approximately 33 years. The oldest district is Central-West District with an average building age of 41 years, while the newest is Anping District, with an average building age of 25 years.

Figure 4. List of basic information of the study area

District	Area (km^2)	Area proportion	Population	Density ($people/km^2$)	Building average age
East District	13.4	7.6%	181,854	13,556	33
South District	28.0	15.9%	120,151	4,285	36
North District	10.4	5.9%	125,801	12,057	33
Annan District	107.2	60.8%	203,882	1,902	28
Anping District	11.1	6.3%	70,435	6,365	25
West Central District	6.2	3.5%	77,212	12,478	41
Total	176.3	100.0%	779,335	4,419	33

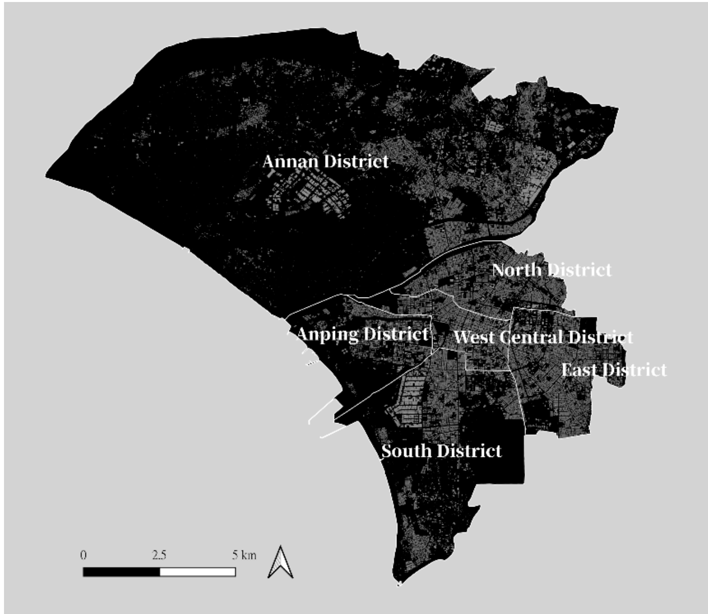

Figure 5. Case Study Area

3.2 Forecasting Trends in REC

Residential electricity consumption trends are analyzed based on historical sales data provided by Taiwan Power Company (Taipower). According to Taipower's statistics, this study calculates annual growth rates from historical sales data and applies these to project future electricity consumption. Due to the revision of statistical formats in September 2020, the classification and data structure before and after this point differ significantly, resulting in inconsistencies. Therefore, data before 2020 are excluded from growth rate calculations. This study uses the average annual growth rate from 2021 to 2024 for each administrative district to estimate future trends. An "exponential growth model" is applied to project residential electricity consumption from 2025 to 2030.

3.3 Correlation Analysis Between REC and Socioeconomic Indicators

To assess the influence of socioeconomic indicators on residential electricity consumption, this study uses residential electricity sales data as the dependent variable, under the assumption that Taipower's electricity sales are equivalent to actual electricity usage. The 2024 residential non-commercial electricity sales data from Taipower are used as the dependent variable.Socioeconomic indicators are used as independent variables, selected based on a review of relevant literature and tailored to the Taiwanese context. Five main dimensions are considered:Children in the household, Age composition of household members, Household size, Educational attainment, Household economic status, Each dimension contains specific evaluation indicators (as detailed in the table below). The most recent available data from official statistical sources are used for analysis.Finally, the data are analyzed using SPSS statistical software to conduct a correlation analysis, examining the statistical significance and direction (positive/negative) of the relationship between each indicator and electricity consumption.

Figure 6. List of socioeconomic indicators in this study

Type	Indicators
Children	• Proportion of population aged 0~15 (2024) • Average number of children per household (0~15 population / number of households) (2024)
Age of household	• Proportion of population aged under 50 (2024) • Proportion of population aged 51~64 (2024) • Proportion of population aged 65 and above (2024)
Household size	• Average number of persons per household (2024)
Education level	• Proportion of permanent residents with higher education (college and above) (2010)
Household income	• Total household income (NTD) (2021)

3.4 Estimation of PV Generation and Self-Sufficiency Rate

This study utilizes government-provided 3D spatial data to estimate the rooftop area of buildings in each administrative district. Relevant parameters are then applied to calculate the potential rooftop photovoltaic (PV) electricity generation for each district. By comparing the estimated annual rooftop PV electricity generation with the residential electricity consumption(REC), the self-sufficiency rate for each district can be calculated. This study proposes several scenario simulations to examine how changes in electricity generation and consumption affect the self-sufficiency rate. These scenarios include variations in generation capacity and residential electricity consumption.

Figure 7. Summary of scenario assumptions

Scenario		Electricity generation	Residential electricity consumption
Baseline	Generation unchanged REC unchanged	10% of the rooftop PV area of existing buildings	Actual REC in 2024
Scenario 1	Generation unchanged REC increased	10% of the rooftop PV area of existing buildings	Estimated REC in 2030
Scenario 2	Generation increased REC increased	25% of the rooftop PV area of existing buildings	Estimated REC in 2030
Scenario 3	Generation increased REC unchanged	25% of the rooftop PV area of existing buildings	Actual REC in 2024

4 RESULTS

4.1 Residential Electricity Consumption Estimate

An analysis of residential electricity sales from 2021 to 2024 in the six districts reveals that Annan District consistently had the highest electricity consumption, followed by East District, with Anping District having the lowest.Regarding growth rates, East, South, and North Districts exhibited negative growth rates from 2021 to 2023, whereas Annan, Anping, and West Central Districts showed positive growth. All six districts showed positive growth between 2023 and 2024.

Based on these trends, the average growth rate over the past three years was calculated for each district. Annan District recorded the highest average growth rate at 2.58%, while East District had the lowest at 0.27%.These results indicate that Annan District not only has the highest consumption but also the fastest growth rate, while East District, despite high consumption, shows signs of a declining growth trend.

Future REC from 2025 to 2030 is projected using the exponential growth model based on the calculated average growth rates.

Figure 8. Average REC growth rate of each district from 2021 to 2024

District	2021~2022	2022~2023	2023~2024	Aerage
East District	-1.5%	-0.5%	2.85%	**0.27%**
South District	-1.7%	0.3%	2.83%	**0.47%**
North District	-1.3%	-0.5%	2.67%	**0.29%**
Annan District	1.2%	1.7%	4.91%	**2.58%**
Anping District	0.4%	0.3%	4.96%	**1.89%**
West Central District	0.4%	0.1%	2.83%	**1.11%**

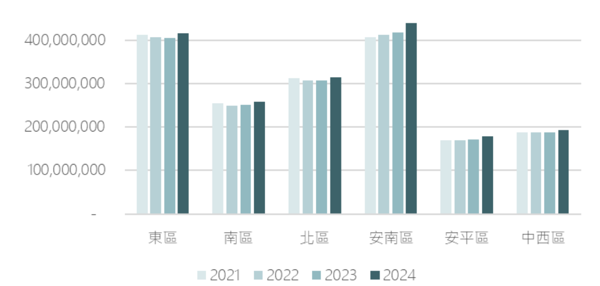

Figure 9. Residential electricity sales from 2021 to 2024

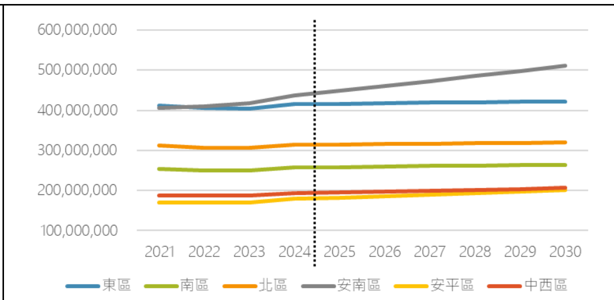

Figure 10. Estimated REC from 2025 to 2030

4.2 Correlation Between REC and Socioeconomic Indicators

Using Pearson correlation analysis, the relationships between eight indicators across five dimensions and residential electricity consumption were examined. The results show that only the variable "Total Household Income" had a statistically significant positive correlation with residential electricity consumption (Pearson r = 0.814, p = 0.049 < 0.05), consistent with findings from prior literature.

All other indicators showed no statistically significant correlation.

Figere 11. Pearson correlation results

Type	Indicators	Pearson correlation	Significance (two.sided)
Children Age of household	Proportion of population aged 0~15 (2024)	0.214	0.683
	Average number of children per household (0~15 population / number of households) (2024)	0.418	0.410
Household size Education level	Proportion of population aged under 50 (2024)	0.507	0.305
	Proportion of population aged 51~64 (2024)	-0.520	0.290
	Proportion of population aged 65 and above (2024)	-0.273	0.601

Type	Indicators	Pearson correlation	Significance (two.sided)
Children	Average number of persons per household (2024)	0.671	0.145
Age of household	Proportion of permanent residents with higher education (college and above) (2010)	-0.046	0.930
Household size	Total household income (NTD) (2021)	0.814	0.049*

* Significance (two.sided) <0.05 was significant

4.3 Estimation of Rooftop PV Generation and Self-Sufficiency Rate Analysis

4.3.1 Estimation of Rooftop PV Generation

The potential solar power generation for each district was estimated by first calculating the available rooftop area using government spatial data, then applying the following formulas:

Estimated Rooftop PV Installation Capacity (kW)= Rooftop area × 0.5 / 10
(0.5: proportion of usable rooftop area; 10 m²/kW: installation density factor)

Estimated Annual Electricity Generation (kWh)= Installation Capacity (kW) × Average Annual Output per kW
(Average = 1,246 kWh/kW)

4.3.2 Self-Sufficiency Rate Analysis

Three different simulation scenarios were conducted to evaluate changes in the self-sufficiency rate.In the most optimistic scenario, Annan District reached a self-sufficiency rate of 40%, while Anping District only reached 17%.The self-sufficiency rate improvement ranged from 27% in Annan to 11% in Anping, highlighting significant regional disparities in the potential for energy self-sufficiency.

Figure 12. Self-sufficiency rate results under different scenarios

District	Baseline	Scenario 1	Scenario 2	Scenario 3
East District	7.82%	7.69%	19.24%	19.55%
South District	12.92%	12.56%	31.40%	32.30%
North District	8.00%	7.86%	19.66%	20.00%
Annan District	16.38%	14.05%	35.13%	40.94%
Anping District	6.81%	6.09%	15.22%	17.03%
West Central District	9.01%	8.43%	21.07%	22.52%

5 DISCUSSION & CONCLUSION

This study focuses on two key analyses:
(1) the relationship between residential electricity consumption and socioeconomic indicators, and
(2) the assessment of self-sufficiency under varying electricity generation and consumption scenarios.

The findings indicate limited correlation between socioeconomic factors and electricity use at the district level, with only household income showing a significant positive correlation.This result implies that households with higher income levels tend to consume more electricity, likely due to greater financial capacity. Conversely, low-income households may be more sensitive to electricity costs, potentially limiting their consumption.The lack of significance among other indicators suggests that the administrative district scale may be too coarse for evaluating the impact of socioeconomic factors on Positive Energy Districts (PEDs). Future research may benefit from using a finer spatial scale, such as village or neighborhood-level data.
Through scenario simulations, significant differences in self-sufficiency rates across districts were observed. These disparities are likely influenced by historical urban development patterns, planning regulations, and urban form, which result in varying building types and demographic compositions.The results confirm that local characteristics play a crucial role in shaping the potential for energy self-sufficiency and that tailored regional approaches are essential for PED development.This study does not yet consider several key factors in the estimation of power generation, including building age, heritage preservation constraints, building types and structures, and the willingness of residents to install rooftop solar panels. Future work will incorporate these variables through data collection and stakeholder engagement.For electricity consumption, future scenarios may include policy targets, residential preferences by building type, or more precise socioeconomic indicators at the village scale, to better estimate regional electricity demand trends.

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