Assessment of Residential Electricity Consumption and Renewable Energy Self-Sufficiency – a Case Study of Tainan, Taiwan

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1 ABSTRACT

Significant carbon dioxide emissions contribute to global issues such as rising temperatures and climate change impacts, which have emerged as a major and urgent global concern. As a result, numerous countries have committed to cutting down the emission of carbon dioxide to achieve low carbon and net zero emissions targets. As we know human activities such as transportation, construction, and electricity consumption significantly contribute to carbon emissions, and they are all in need of energy. Hence, it's important for every country to use clean energy to transform from low carbon to net zero emissions.

The transformation to renewable energy sources, particularly solar energy, has become a global imperative to combat climate change. However, in Taiwan, despite favorable conditions for solar energy development, there are challenges regarding the policy direction and spatial planning of PV (photovoltaics) installations. The current focus on ground-mounted PV, primarily in rural areas, has raised concerns about land use, environmental impact, and social equity. As a result, there is a pressing need to prioritize PV development in built-up areas to minimize conflicts with green resources and ensure sustainable land use, so the potential of rooftop PV is vital to built-up areas. This study uses Tainan, Taiwan, as a case study area, and the objective is to forecast electricity consumption in the residential and commercial sectors, evaluate the potential for rooftop PV development, and assess the feasibility of achieving renewable energy self-sufficiency in built-up areas. It also examines the electricity consumption patterns and rooftop PV generation potential in different urbanization contexts, emphasizing the need for tailored policies and regulations to promote fair and just renewable energy development.

The research highlights the importance of managing land resources judiciously and implementing policies that prioritize PV deployment in urban and rural built environments. In conclusion, the study underscores the urgency of addressing the spatial, environmental, and social implications of PV development in Taiwan to achieve sustainable energy transition goals. The findings are intended to provide a reference for integrating low-carbon principles into urban management plans. Furthermore, employing growth management as a tool for urban energy management is vital to ensure that renewable energy development adheres to rational processes and standards while protecting environmental resources.

Keywords: Residential Electricity Consumption, Renewable Energy Self-sufficiency, Rooftop Photovoltaic, Low Carbon City, Solar Energy

2 INTRODUCTION

After the Industrial Revolution, the widespread burning of fossil fuels led to significant carbon dioxide emissions, exacerbating global issues such as rising temperatures. The resulting climate change, directly caused by carbon emissions, has become a major and urgent global concern. Consequently, many countries have committed to achieving low-carbon and net-zero emission goals. To transform from traditional, non-renewable energy sources like coal to renewable energy sources and eventually achieve complete reliance on renewable energy for electricity generation, clear policy directions are essential. Moreover, due to the finite nature of land resources, these policies must be effectively implemented in spatial contexts.

The availability of land resources, building conditions, and people's lifestyles, all are influenced by different geographic environments and levels of urban development. They are crucial factors affecting the direction and types of renewable energy development. Therefore, clear spatial planning and layout play important roles in energy transition. Guiding the development of renewable energy fairly and justly is a crucial issue that all countries must address.

Taiwan is in a subtropical climate, so in the development of various renewable energy sources, we have high potential and conditions for installing PV. Therefore, solar energy development is one of Taiwan's primary goals in its energy transition policy. However, due to the lack of clarity in policies and locations, the current situation of solar energy development in Taiwan mainly focuses on large-scale ground-mounted PV and concentrates in rural areas. As a result, the PV encroaches upon agricultural and forestry land, leading to landscape destruction and other issues.

However, the proportion of solar energy development in the built environment, where humans live and reside, is relatively low. Therefore, it is evident that Taiwan faces issues of disorder and conflicts with green resources in solar energy development, which need to be urgently addressed and resolved.

2.1 The justice in the development of PV

2.1.1 The importance of managing the land resources

From the perspective of Nature-based Solutions(NbS) and land ethics, environmental resources should be valued and protected more because the land available to each country is limited, especially agricultural land, fish ponds, or forests, which are natural resources. If the land is converted, it may lose its original fertility, so the best approach is to minimize the impact on environmental resources. In the development of solar energy, PV should avoid being installed on land that provides environmental resources. Large-scale installation of PV on agricultural land or fish ponds not only severely damages rural landscapes but also raises concerns about whether the materials and cleaning processes of the PV may pollute the land. A more serious issue is that this PV may encroach on the production space of agriculture and fisheries, potentially leading to issues with the country's food production space and security.

Therefore, if PV could be installed as much as possible in urban or rural built-up areas, exhausting the electricity generation capacity of built environments and newly developed areas, and only then moving on to adopting agrivoltaic farm, fishery, and electricity symbiosis, or converting agricultural land. As a result, it is crucial to establish the correct solar energy development policies, so it can ensure the sustainability of the land and fair development of renewable energy.

2.1.2 The policies of PV and current development issues in Taiwan

Taiwan is actively promoting the transition to renewable energy with the global goal of achieving net zero emissions. It has set a target that by 2025, 20% of Taiwan's total electricity generation will come from renewable sources, with a total installed capacity target of 29 GW. Given Taiwan's favorable climate conditions, there is a strong emphasis on the deployment of PV, with a target capacity of 20 GW for PV and 5.6 GW for offshore wind power. Within the PV capacity target of 20 GW, 8 GW is allocated for rooftop PV and 12 GW for ground-mounted PV.

According to government planning objectives, Taiwan aims to achieve a capacity of 14 GW by 2023, with approximately 11.66 GW already installed as of October 2023. The capacity of rooftop PV has increased from 1.14 GW in 2016 to 7.33 GW in 2023. Future efforts will focus on installing PV on agricultural facilities, public buildings, school campuses, industrial rooftops, and community rooftops. On the other hand, ground-mounted PV capacity has increased from 0.078 GW in 2016 to 4.33 GW in 2023. The government aims to prioritize projects with societal consensus and no environmental or ecological disputes.

While the capacity of rooftop PV is relatively close to the target compared to ground-mounted PV, there is still a need to install approximately 7.67 GW of ground-mounted PV to meet the 2025 goals. However, the lack of long-term and substantive targets, as well as unclear planning principles and locations, raises significant concerns about potential impacts on vulnerable communities or land resources in the future.

Tainan City is one of the southern cities in Taiwan, which has been actively installing PV and has the highest installed capacity of PV in Taiwan, approximately 2.39 GW. However, many of these installations are observed to be large-scale PV set up on fishponds and agricultural land (Fig. 1). Despite government efforts to address threats to ecology or communities from fishery and electricity symbiosis projects through regulations and stakeholder engagement, these measures are seen as reactive rather than proactive. Additionally, the lack of clear long-term development goals and spatial planning in Tainan has led to the over-installation of solar panels in some areas, prompting residents to protest and demand a more proactive and positive response from the government regarding PV development. (Fig. 2)

In Taiwan's pursuit of energy transition, decarbonization, and sustainability, focusing solely on achieving the total installed capacity of PV without considering broader issues of land use and equity has resulted in conflicts with green resources. Thus, it underscores the importance of prioritizing the development of PV in built-up environments and the need for a comprehensive and prioritized approach to PV development. Taiwan has a similar area and population to the Netherlands, but the Netherlands' national vision plan, which emphasizes diverse development approaches based on the limited land area, thereby minimizing environmental impacts. Utilizing existing buildings in urban areas as sites for PV generation not only avoids unfair impacts on vulnerable areas or environmental resources but also enhances land use efficiency to ensure the sustainability of land resources. Moreover, integrating rooftop PV with energy storage technology and smart grids can change the traditional unidirectional power supply, helping urban areas have more stable power and reducing the risks of unstable renewable energy supply and transmission losses.


Fig. 1 (left): Ground–mounted PV in Taiwan (source: China Daily News). Fig. 2 (right): People protest excessive development of ground–mounted PV (source: Qigu Dist. Supervisory Optoelectronics Youth Alliance Facebook).

2.2 Electricity consumption and rooftop PV in built-up areas

Taking into account the summarized issues from the previous discussion, it is evident that the development of solar PV in built-up areas will be an important topic for exploration. Therefore, there should be efforts to identify the maximum potential for PV generation in built-up areas and explore the energy self-sufficiency achievable through PV generation under actual electricity consumption scenarios. This information can serve as a reference for subsequent policy formulation regarding PV development.

Currently, in built-up areas, Taiwan primarily focuses on rooftop PV, utilizing the roofs of buildings as space for solar panel installations to avoid direct land disturbance. This approach also creates opportunities for individuals to generate and sell electricity using solar panels, thereby promoting economic benefits and creating new job opportunities. However, compared to abroad where various types of buildings are gradually equipped with solar panels, Taiwan's regulations for rooftop PV only mandate certain scale buildings to install a certain proportion of solar panels.

To ensure that the development of renewable energy aligns more closely with principles of fairness and justice, there should be greater encouragement for the installation of rooftop PV in built-up areas. Therefore, this research aims to explore electricity self-sufficiency in built-up areas.

2.2.1 <u>The degree of urbanization causes differences in electricity consumption and PV generation potential</u>

Analyzing the overall electricity usage in a country can be broadly categorized into domestic usage and industrial usage. Domestic usage includes residential and commercial usage. Industrial usage includes primary industries and manufacturing. From preliminary analysis, it is evident that domestic usage is more universal and consistent compared to industrial usage. Industrial usage varies significantly based on the industry type and scale, making it less predictable and requiring regional power regulation to achieve balance. On the other hand, domestic usage is influenced by population density and development scale, making it relatively predictable. In urban areas, electricity usage is generally higher due to denser populations and diverse activities, resulting in more tall buildings and compact distribution (Fig. 3). Conversely, rural areas have lower population density, less diverse activities, and scattered, low buildings (Fig. 4), leading to lower electricity usage compared to urban areas.

Regarding the PV generation potential, built-up areas also vary in their suitability for generation due to differences in characteristics. For instance, urban areas with many tall and densely packed buildings may have reduced potential for rooftop PV installation due to shading issues. Additionally, older buildings may have limitations on installing rooftop solar panels. In contrast, rural areas with more dispersed buildings and available land may have a higher potential for PV installation. As a result, considering regional differences in electricity usage and PV generation potential, statistical analysis and forecasting of both supply and demand sides are necessary to effectively promote PV development. This information can inform tailored policies and regulations to promote fair and just renewable energy development.

Fig. 3 (left): Urban area landscape in Taiwan (source: ETtoday News). Fig. 4 (right): Rural area landscape in Taiwan (source: taiwanhot).

2.2.2 The policies of rooftop PV and prospect in Taiwan and Tainan

Countries like Canada, Japan, and Germany have enacted laws to encourage and promote rooftop PV. For instance, in 2009, Toronto, Canada, introduced Chapter 492 of the Toronto Municipal Code, known as the Green Roofs. This law mandates that new buildings, new development zones, and residential projects with a total floor area exceeding 2,000 square meters constructed after 2010 must utilize 20-60% of rooftop space for greenery or solar panels. Similarly, Berlin, Germany, implemented the Berlin Solar Law in 2021, requiring new, expanded, or renovated buildings with a footprint exceeding 50 square meters to install solar panels covering at least 30% of the rooftop's net area.

In Taiwan, some Non-Governmental Organizations advocate for the principle of "urban electricity from urban areas" to promote regional development equity (Fig. 5). They propose incorporating rooftop PV into the law to prevent extensive solar panel coverage of environmental resources and excessive concentration in rural areas. Therefore, promoting the self-sufficiency of energy in residential and commercial areas within built-up areas is a key goal for Taiwan's future. However, in the subsequent legislative proposals, the Legislative Yuan stipulates that buildings with an area of 1,000 square meters or more, whether new, expanded, or renovated, must install 1 kW of solar power for every 20 square meters. This approach primarily targets large-scale PV, unlike Germany's law, which includes smaller residential buildings.

Fig. 5 (left): People advocate inclusion of rooftop PV in regulations (source: Citizen of the Earth, Taiwan.). Fig. 6 (right): Community rooftop PV in Taiwan (source: Yahoo News).

Taiwan is currently implementing the "Green Roof All-Participation" program for small-scale buildings like residences, aiming to realize the concept of a citizen power plant by encouraging rooftop solar adoption. In Taiwan's current system, after building owners install solar panels, the electricity generated is not for their own building's use. Instead, the government guarantees to purchase green energy at a higher price, providing a certain incentive. As a result, regardless of whether the building owners are the ones using electricity for the actual building, it is beneficial to install PV as long as time and environmental conditions permit. However, single-building initiatives may result in energy inefficiencies or low economic benefits due to their small scale, leading to reduced interest among the public. Therefore, future policy and regulatory frameworks should emphasize community-level renewable energy systems planning for entire neighborhoods or communities to enhance flexibility in energy supply and demand (Fig. 6). Additionally, policymakers should incentivize the comprehensive renewal of older communities to promote the widespread adoption of rooftop solar in built-up areas.

3 METHODOLOGY

This study selects Tainan City as the empirical research base site, which has the highest installed PV capacity in Taiwan (Fig. 8). Tainan, located in an area with abundant sunlight, is an excellent location for PV development. Geographically, Tainan's terrain is higher in the east and lower in the west, leading to a natural tendency for people to reside in the flatlands to the west (Fig. 9). As a result, urbanization levels radiate outward from the city center on the southwest side, causing uneven population distribution spatially.

However, current data indicates that PV development in Tainan primarily occurs in rural areas on agricultural land and fish ponds. Some solar panels are situated very close to habitats of important wildlife species, resulting in changes to their habitats and potential inconveniences for residents. The current PV development in Tainan does not prioritize rooftop PV installations, highlighting the need to confirm whether rooftop PV development in built-up areas can meet the electricity demand of residential and commercial sectors. It is also need to analyze the feasibility of achieving energy self-sufficiency through rooftop PV in areas with different levels of urbanization. Future efforts will focus on formulating fair regulations to ensure the development of renewable energy aligns with principles of justice.

Therefore, this study will be divided into three parts. The first part involves analyzing electricity consumption patterns, focusing on residential and small-scale commercial buildings in built-up areas to assess whether electricity usage differs across areas with varying degrees of urbanization. The second part explores the PV generation potential in built-up areas. Considering factors like building age, form, and density, the study will simulate different scenarios to understand the PV generation potential of rooftops. The third part calculates the self-sufficiency rate of electricity by comparing the power supply and demand in areas with different levels of urbanization. These results will serve as references for formulating future renewable energy development strategies based on regional characteristics and conditions.

(1) Calculation of Actual Electricity Demand

To understand the electricity consumption trends in a specific area, this study will analyze residential and commercial electricity sales data collected by the Taiwan Power Company over the past five years (2018-2022). In addition to analyzing electricity consumption trends in various areas, the data will be inputted into GIS systems for spatial analysis.

(2) Simulation of PV Generation Potential on Different Building Rooftops

To further understand how urbanization levels affect electricity consumption, this study will select three administrative districts—West Central District, Qigu District, and Longqi District—as the main research areas based on their urbanization levels. Given that the lifespan of PV is approximately 20 years and buildings typically have a lifespan of 50 years, different scenarios will be simulated to calculate the PV generation potential of rooftops. The first scenario assumes that buildings older than 30 years will not be considered, and only relatively new buildings (30 years old or less) will have solar panels installed. The second scenario assumes that both new and old buildings will have rooftop PV installed, with older buildings also being retrofitted with PV. Similarly, solar panels will cover 50% of the projected area of the building in both scenarios to analyze the potential generation capacity in built-up areas.

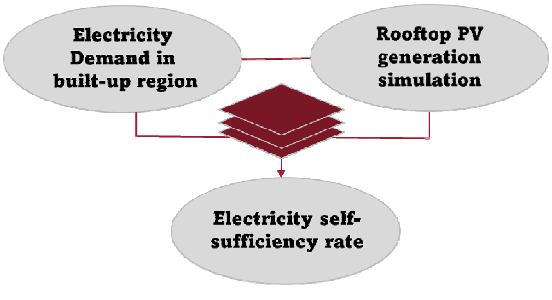


Fig. 7: Schematic diagram of research methods

(3) Calculation of Electricity Self-Sufficiency Rate

By combining the results of the first two steps, the electricity consumption and potential supply of electricity in a specific area can be determined. These results will then be used to analyze the electricity self-sufficiency rate in different regions.

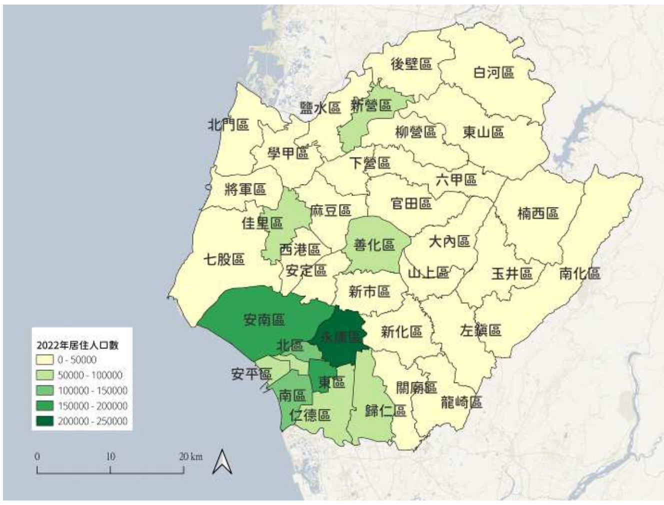


Fig. 8 (left): Aerial photo of Tainan City. Fig. 9 (right): Tainan City population distribution map in 2022

4 ELECTRICITY CONSUMPTION

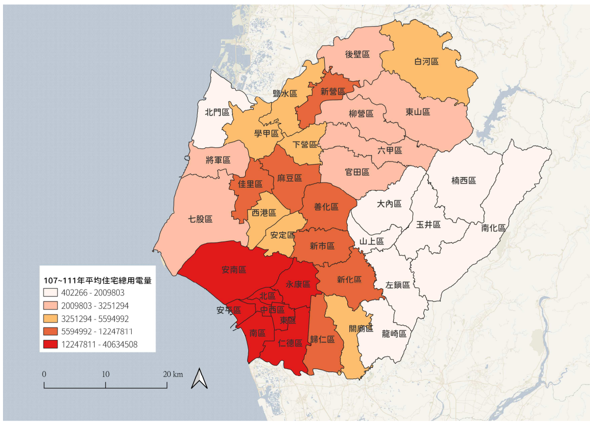
4.1 Distribution of electricity consumption in residential and commercial sectors

Based on the statistical data from the Taiwan Power Company for the years 2018 to 2022, an analysis of the pure residential electricity consumption in various districts of Tainan City reveals a strong correlation between residential electricity usage and the degree of urbanization. The areas which are highlighted in red (Fig. 10), particularly concentrated in the southwest, represent the city center of Tainan and exhibit the highest levels of electricity consumption, which gradually diminishes outward. In contrast, the white areas on the eastern side, closer to the mountainous regions, demonstrate lower electricity consumption and reflect the lower population density in these rural areas. This underscores the fact that urban areas exhibit higher electricity demand due to their larger populations.

Due to the high degree of mixed land use in Taiwan, there is no clear boundary between residential and commercial buildings in the city. Therefore, to be more consistent with the domestic electricity consumption in the city, this study investigated the electricity consumption of low-voltage electricity in residential and small businesses. According to research results, particularly prevalent in urban areas with more intensive commercial activities, the analysis still confirms that urban regions exhibit relatively higher electricity demand compared to rural areas (Fig. 11). In contrast, rural areas tend to have lower intensity in commercial development, suggesting a lower electricity consumption. This highlights both the higher electricity demand in urban areas compared to rural ones and the potential for greater energy conservation and efficiency measures in urban settings.

4.2 Average monthly electricity consumption of each residential household and classification

After dividing the total electricity consumption of pure residential areas by the number of households, the average monthly electricity consumption per household can be calculated. Visualizing this data reveals a correlation with the degree of urbanization, where more urbanized areas tend to have higher average monthly electricity consumption per household (Fig. 12). However, when calculating the average residential electricity consumption per capita, it can be found that there is no significant correlation with urbanization. However, the average residential electricity consumption per capita in areas with high urbanization is still high. On the contrary, in some suburbs, the average residential electricity consumption per capita is also high. This means that although the total electricity consumption in these areas is small, the average electricity consumption is high because the number of people is also small (Fig. 12).



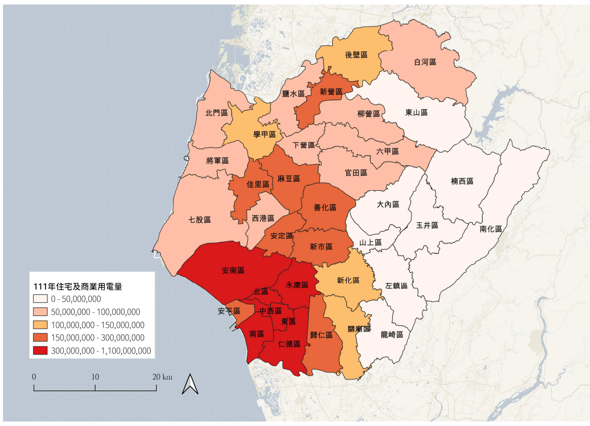
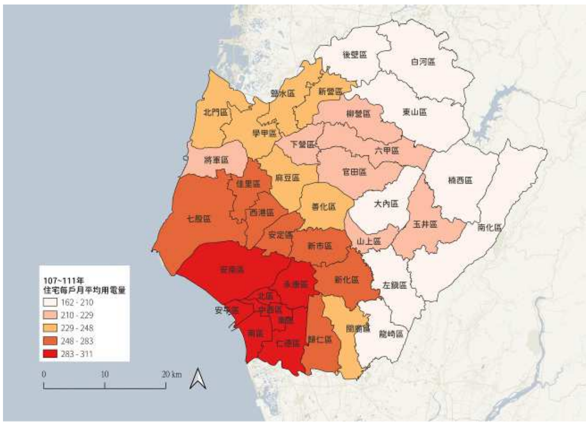


Fig. 10 (left): Average total electricity consumption of residential buildings in Tainan City from 2018 to 2022. Fig. 11 (right): Total electricity consumption of low-voltage electricity buildings in Tainan City in 2022.

Therefore, further categorization of Tainan's administrative districts based on their urbanization level and characteristics reveals five types, with each household's monthly average electricity consumption ranging from 188 kWh to 291 kWh (Fig. 14). The downtown area, characterized by the highest level of urbanization, constitutes the first category, with an average monthly electricity consumption of approximately 291 kWh per household. The second category comprises the peripheral areas surrounding the downtown, with an average monthly electricity consumption of around 260 kWh per household. The third category consists mainly of agricultural areas across the district, with an average monthly electricity consumption of about 240 kWh per household. The fourth category, dominated by agricultural zones and hilly terrain, records an average monthly electricity consumption of approximately 214 kWh per household. Finally, the fifth category represents areas with the lowest urbanization level, predominantly consisting of hilly terrain and forests, with an average monthly electricity consumption of around 188 kWh per household. (Table 1)



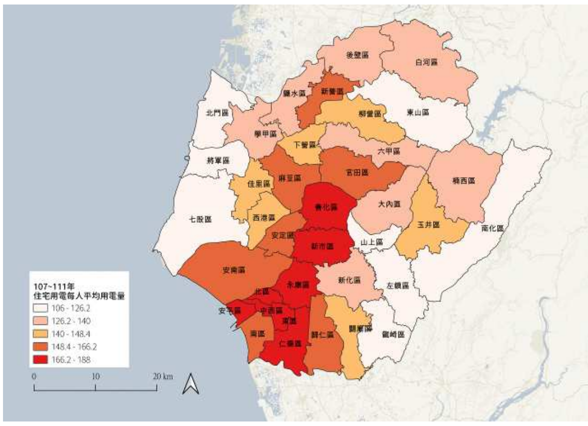


Fig. 12 (left): Average monthly residential electricity consumption per household from 2018 to 2022 in each administrative district of Tainan City. Fig. 13 (right): Average residential electricity consumption per capita from 2018 to 2022 in each administrative district of Tainan City

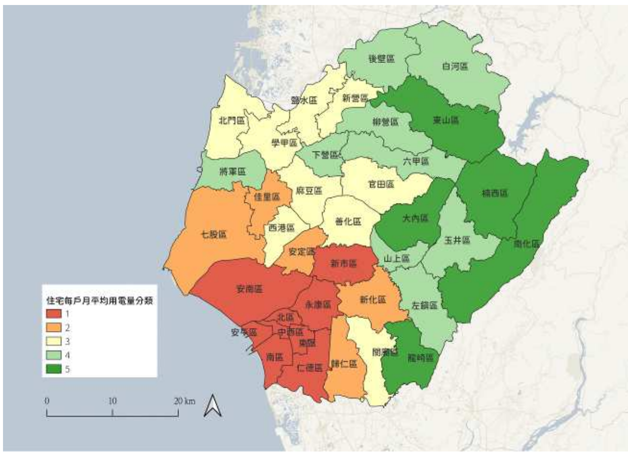


Fig. 14: Classification of administrative districts in Tainan City

Type	Illustration	Average monthly residential electricity consumption per household (kWh)
First category (1)	It has the highest degree of urbanization and is in the city center. The entire area or most of the area is a city (town) plan or urban plan.	290.63
Second category (2)	It is in peripheral areas surrounding the downtown.	259.88
Third category (3)	The whole area is mainly agricultural areas.	239.67
Fourth category (4)	The entire area is dominated by hillside conservation zones and agricultural areas.	213.97
Fifth category (5)	The degree of urbanization is the lowest, and almost the entire area belongs to forest areas or hillside conservation zones.	188.42

Table 1: Classification of average monthly residential electricity consumption per household in each administrative district of Tainan City

5 ROOFTOP PV POTENTIAL AND ELECTRICITY SELF-SUFFICIENCY

To further analyze the electricity self-sufficiency rates of different types of built-up areas, this study selects representative districts from among the 37 administrative districts of Tainan City. The first category, representing areas with the highest degree of urbanization, is represented by the West Central District. The second category, representing suburban areas outside the urban center, is represented by the Qigu District. Lastly, category 5 which is areas with low levels of urbanization, predominantly hilly terrain and forest areas, is represented by the Longqi District.

The study begins by analyzing the distribution density, number of floors, and age of buildings in these three types of areas to determine if there are significant differences. Subsequently, simulations of the potential for PV generation based on two scenarios are conducted to explore the achievement of residential and commercial electricity self-sufficiency rates in the three types of urbanized areas.

5.1 Overview of buildings' condition in each district

The West Central District, located in the old city area of Tainan City, exhibits a high degree of urbanization, resulting in dense building distribution (Fig. 15). Legally constructed building areas account for 31.54% of the total administrative district area, with buildings primarily ranging from 3 to 5 stories in height. Buildings with an age of under 30 years represent only 37.62% of the total building area.

The Qigu District, situated in the suburban area, is primarily characterized by fishpond usage due to its proximity to the Taiwan Strait. As a result, buildings are widely dispersed (Fig. 16), and settlements are concentrated in areas closer to the inland eastern side. Legally constructed building areas comprise only 0.43% of the total administrative district area, with buildings mostly consisting of 2 stories or fewer. Buildings with an age of under 30 years represent approximately 68.30% of the total building area.

District	Legally constructed building density	The ratio of buildings with an age of under 30 years	Ratio of buildings below 2 stories	The ratio of buildings between 3~5 stories	Ratio of buildings above 5 stories
West Central District	31.54%	37.62%	40%	46.1%	13.9%
Qigu District	0.43%	68.30%	78.9%	21.1%	0%
Longqi District	0.10%	42.58%	95.2%	4.8%	0%

Table 2: Buildings analysis in West Central District, Qigu District and Longqi District

The Longqi District, adjacent to the Central Mountain Range, features more sloped terrain and forested areas, resulting in even more scattered building distribution (Fig. 17). There are no distinct settlement patterns, and legally constructed building areas account for only 0.1% of the total administrative district area.

Buildings in this area mostly consist of 2 stories or fewer, with buildings under 30 years of age constituting around 42.58% of the total building area.

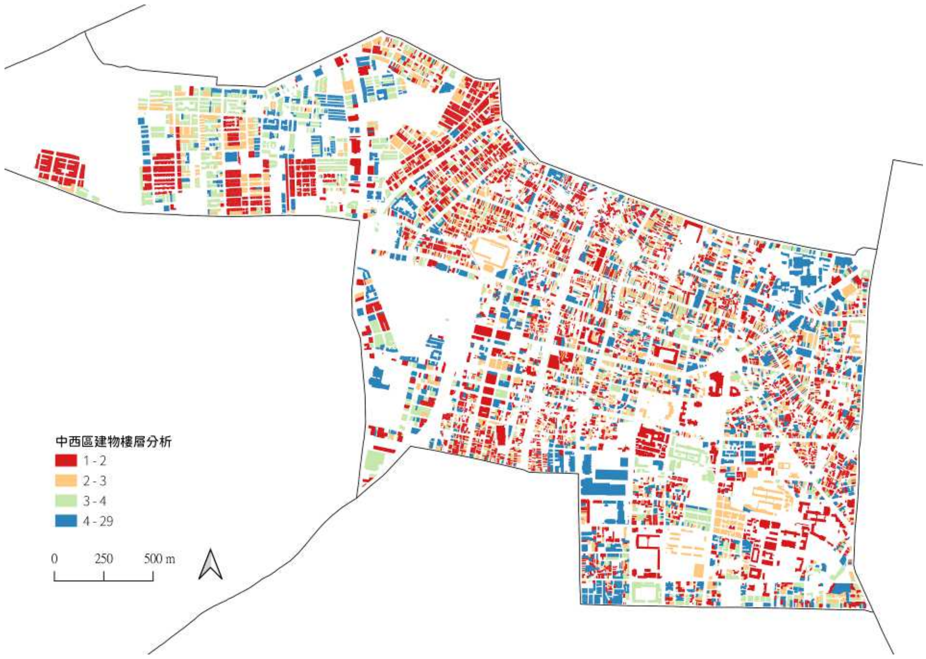
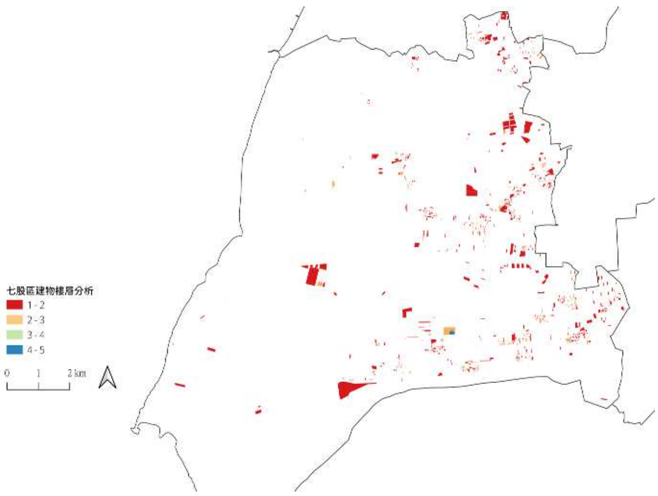


Fig. 15: Building height analysis in West Central District



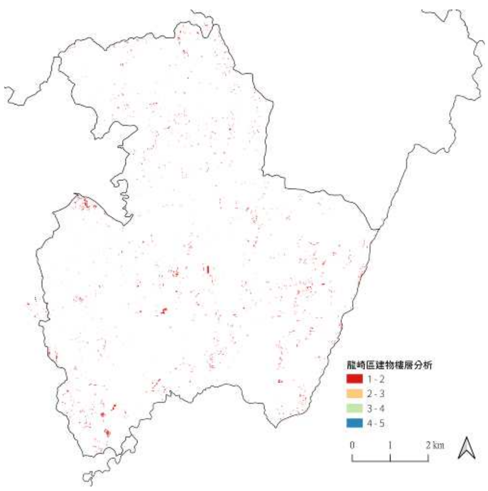


Fig. 16 (left): Building height analysis in Qigu District. Fig. 17 (right): Building height analysis in Longqi District

5.2 Rooftop PV potential and electricity self- sufficiency rate

In the calculation of rooftop PV potential, based on 50% of the projected area of legal buildings in the West Central District, Qigu District, and Longqi District, two scenarios are simulated to calculate the potential for rooftop PV development to meet actual electricity demand. This serves as a basis for formulating tailored goals and policies for solar PV development in urban and rural areas.

The rooftop PV potential is divided into two scenarios, considering that the average lifespan of buildings is 50 years while rooftop PV systems have a lifespan of 20 years. In the first scenario, the potential supply area for rooftop PV is calculated based on buildings under 30 years old, covering 50% of the total roof area. In the second scenario, it is assumed that all buildings can install solar panels in the future, with the same calculation method applied.

For the self-sufficiency rate calculation, the electricity usage from 2022 for low-voltage buildings is considered to better reflect general electricity consumption patterns. The results of the self-sufficiency rate calculation show that in the first scenario, the West Central District, which has a higher degree of urbanization and older buildings, has the lowest self-sufficiency rate at only 13%. In contrast, the Qigu District achieves the highest rate at approximately 26%, while the Longqi District reaches 23%. In the second scenario, with increased potential for rooftop PV, the self-sufficiency rates improve. The West Central District increases to 33%, the Qigu District to 39%, and the Longqi District sees the most significant improvement, rising to 54%.

Comparing self-sufficiency rates across different types of built-up areas reveals that while the West Central District has more buildings, its urban electricity consumption is higher, resulting in a maximum self-sufficiency rate of only 33%. Conversely, rural areas like the Longqi District, despite having fewer rooftops suitable for solar panels, achieve higher self-sufficiency rates of up to 54%, indicating greater potential for renewable energy self-sufficiency in rural areas. Therefore, efforts to promote rooftop PV installation should be strengthened in rural areas.

District	Electricity consumption of low-voltage buildings in 2022(kWh)	Rooftop PV power generation of buildings under 30 years old (kWh)	Self-sufficiency rate	Rooftop PV power generation of all buildings (kWh)	Self-sufficiency rate
West Central District	384,294,465	48,125,802	13%	127,919,393	33%
Qigu District	80,067,651	21,118,247	26%	30,921,360	39%
Longqi District	7,456,496	1,720,407	23%	4,040,161	54%

Table 3: Rooftop PV potential and self-sufficiency rate in West Central District, Qigu District, and Longqi District

6 CONCLUSION

In Taiwan, solar energy has been a development goal in recent years. However, the government has focused solely on the target of installed PV capacity, lacking long-term policy goals and a reevaluation of energy supply and demand. This has led to the current phenomenon of disorderly development in PV facilities, with large-scale ground-mounted PV installations encroaching upon agricultural land or fish ponds, raising concerns about the destruction of green and ecological resources. Therefore, the development of renewable energy and the logic of land ethics and land planning must be established to avoid aggressively promoting energy transformation while damaging important national land resources. Currently, Taiwan has set a target of 20GW of installed PV capacity by 2025, without clear spatial planning or development strategies and guidance for different types of areas. With the population growth and construction of new buildings in different regions, failure to promptly establish appropriate policies to make the most of these built-up areas could lead to a continuous increase in the amount of electricity that ground-mounted PV must generate. Therefore, the promotion of rooftop PV should be given more attention and foresight, but it should not lack a careful evaluation process.

This study attempts to explore the self-sufficiency rate of rooftop PV based on residential and commercial electricity consumption in built-up areas. From the results of this study, rural areas have a high potential to achieve self-sufficiency in electricity consumption through rooftop PV, thus future efforts should focus on promoting electricity self-sufficiency in rural areas. Although the degree of self-sufficiency in urban areas is limited, the high population and building density in cities also provide opportunities to reduce electricity demand through energy-saving measures. Additionally, renewable energy generation, including solar PV, is relatively unstable compared to traditional coal-fired or nuclear power generation and is also time-dependent. Therefore, the stability of the future power system is crucial. Currently, Taiwan's electricity distribution is mainly centralized production by Taiwan Power Company, distributed to households or industries, posing high risks and energy losses in a centralized power grid. Electricity has always been essential for human life, production, and transportation. Rooftop PV provides an opportunity for power system reform by increasing the popularity of distributed energy sources through public participation, allowing local power needs to be produced locally, and ensuring the efficient use of energy. As a result, urban areas should also re-examine urban infrastructure, actively promote the development of community-based PV installations, and complement them with energy storage and smart grid deployment to improve grid layout, reduce unidirectional power transmission, and increase electricity efficiency in urban areas.

In terms of future research recommendations, because this study only focuses on the potential of rooftop PV installations in built-up areas, it has not considered other renewable energy sources that could be developed in built-up areas, such as small wind power and small hydroelectric power. Additionally, with technological advancements, buildings can integrate solar energy not only on rooftops but also on facades through Building-Integrated Photovoltaics (BIPV). Therefore, future research on renewable energy simulations in established areas could explore more diverse scenarios. In legal terms, other possible renewable energy sources should be included, and the integration of solar energy into buildings should be encouraged, rather than just focusing on rooftop PV. In conclusion, specific regions should not bear greater sacrifices, and appropriate regulatory measures should be used to maximize the use of available buildings and spaces in built-up areas, allowing areas needing electricity to generate their own power, and reduce unnecessary damage to environmental resources. If electricity self-sufficiency cannot be achieved within built-up areas, the government should use growth management measures to maintain fair development between regions, achieving a more just development of renewable energy.

7 REFERENCES

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