

The impact of shadow covering on the rooftop solar photovoltaic system for evaluating self-sufficiency rate in the concept of nearly zero energy building

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ABSTRACT

In cities seeking energy self-sufficiency, one of the trends is to pursue nearly zero-energy buildings (nZEB). To achieve this target, reducing energy consumption as well as replacing the traditional energy by renewable energy are two major strategies. The former is limited by the difficulty in lowering energy consumption in daily life, so the latter has more potential. Solar photovoltaic systems are a popular means to reach the goal of self-sufficiency in cities, and those on rooftops have the highest efficiency. Shadow from surrounding buildings affects the energy generation but this research found that the impact of shadow is generally limited. Only buildings of less than 3 storeys might suffer serious shadow covering and those higher than this mainly reduce their productivity by only about 1%. However, although lower buildings experience shadow effects, they are the main energy generators due to their low energy self-consumption. For example, the energy shortage of the tallest building in this case study could be covered by a 1-storey building with 10.33 times area. This research indicated that a fully energy self-sufficient environment can be achieved when the city pattern is designed with consideration of a well-balanced building height arrangement.

1. Introduction

Traditional energy, such as fossil fuel or coal-fired power plant, meets the demand of city development, but it also produces hazardous greenhouse gases and accelerates climate change. Cities are places clustering more than 50% of the population and consuming most of the power (UN, 2013); meanwhile, the European Union (EU) has pointed out that, for the total power consumption, buildings account for about 40% of the energy demand (EUR-Lex, 2010). To reduce the traditional energy dependency in buildings and slow down the threat from greenhouse gases as well as climate change, the EU established a guideline and set energy-saving targets year by year under the concept of nearly zero-energy building (nZEB) (EUR-Lex, 2010, 2018). In this concept, two main ways have been practised to reach the target: decreasing the power consumption (Aksamija, 2015; Hadorn, 2015; Schimschar et al., 2011; Sudhakar et al., 2019; Yi et al., 2017; Zhang et al., 2014) and replacing the traditional energy sources with renewable energy systems (Aelenei & Gonçalves, 2014; Hasan & Mohamed, 2015; Liu et al., 2019; Luthander et al., 2016; Oliveira Panão et al., 2013; Petersen, 2016; Reis et al., 2019; Shukla et al., 2016). The former method mainly focuses on

the building itself, covering the building envelope and the support system. Architects will adopt new building materials or techniques that are low-CO₂ producing or have better insulation efficiency when undertaking construction or renovation (D'Agostino et al., 2016; Hernandez and Kenny, 2010; Sartori et al., 2012; Semprini et al., 2017; Yung et al., 2013). Meanwhile, the supporting system, including heating, hot water, air conditioning, ventilation, lighting, and all of the daily necessities, can also be replaced by other systems whose energy efficiency is higher (Aksamija, 2015; Yi et al., 2017). The latter, in another perspective, creates an energy self-sufficient system that does not only rely on the traditional energy power grid (Luthander et al., 2016; Merei et al., 2016; Sartori et al., 2012).

From the perspective of reducing power consumption, when this involves building structure such as the building envelope, renovation or equipment installation, it can be considered as embodied energy (EE) (Alwan & Jones, 2014; Chastas et al., 2016; Giordano et al., 2017; Vares et al., 2019), whereas the consumption that is a consistent requirement for living, including all of the supporting systems, can be categorised as the primary (D'Agostino & Mazzarella, 2019; Oliveira Panão et al., 2013; Schimschar et al., 2011) or operational energy (OE) (Giordano

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et al., 2017; Hernandez & Kenny, 2011). Although energy consumption can be separated into these two types, there is a mutual relation between them Hernandez and Kenny (2011). have indicated that to reach better OE efficiency, better building materials, which always imply more energy consumption, should be used. EE is one of the largest parts of the total energy consumption during the whole life cycle of the building. To measure it properly, it is generally split into years of depreciation, mainly over a 50-year period (Chastas et al., 2016), to spread the cost. Considering the idea of reducing greenhouse gas emissions and reaching the target of nZEB, both EE and OE should be included (Yi et al., 2017). However, based on the Directive 2010/31/EU, only the primary energy (OE) is to be measured (EUR-Lex, 2010) due to the problematic and complex estimation of EE (Giordano et al., 2017). In present, the target group in this resolution focuses on new construction, but buildings over 50 years old are quite common in the EU (Semprini et al., 2017). EE from the initial construction of those buildings would be assumed as zero because they have reached the end of the depreciation period. Including EE in the cost would make an uneven standard between old and new buildings when evaluating the level of zero-energy. The reduction of both EE and OE is helpful for reaching the target of nZEB, but renewable energy is still necessary to cover the remaining energy consumption (Oliveira Panão et al., 2013) due to the limited scope for energy reduction.

Among the replacement renewable energy resources, solar energy is one of the most popular (Murdock et al., 2020; Schimschar et al., 2011). The small units required make them easy to install on homes (Kouhes-tani et al., 2019). From the perspective of greenhouse gas emissions, Kumar (2017) indicated that a solar photovoltaic (PV) system will generate only one-sixth and one-tenth of the CO₂ of gas and coal, respectively compared to traditional energy, and this level of emission was measured at the time of producing the solar plant. Since no additional greenhouse gas would be produced during actual power generation, the total cost could be considered as EE rather than OE. Four factors are involved when adopting solar PV as the renewable energy resource: solar irradiation, the condition of the radiation receiving area, the shadowing effect, and the energy transfer rate. The intensity of solar irradiation is generally inverse to the latitude, and the meteorological condition is also a variable. Its measurement can be done by satellite survey (Perez et al., 2002; Pfeifroth et al., 2018; Urraca et al., 2017) and local meteorological stations (Biljecki et al., 2015; Ko et al., 2015). To make the result close to the real surface condition, the former data can be transformed through a clear-sky model and cloud index (Cano et al., 1986; Gueymard, 2008; Perez et al., 2002; Reno & Hansen, 2014), and the adjusted number is then reorganised as the Typical Meteorological Year (TMY) data to represent the general weather condition (Gagnon et al., 2016; Ho et al., 2013). Radiation receiving areas are mainly of two types in the city: rooftop and façade. PV panels on rooftops have the flexibility to adjust the inclination angle and the orientation in order to pursue the most intense solar irradiation, whereas those on façades are always vertical to the ground. Due to the weak inclination angle, solar panels on façades have a weaker power generating efficiency than those on rooftops (Amado & Poggi, 2012; Redweik et al., 2013; Sarralde et al., 2015). On the other hand, shadow is another factor that increases this gap. The city pattern creates various shadow effects, and the surface of a vertical building can easily be blocked by surrounding construction. When the distribution of building heights is uneven or buildings have ridges, this will have an impact on the rooftops (Natanian & Auer, 2020; Yuan et al., 2016; Zhong & Tong, 2020). The energy transfer rate varies depending on the construction material and technology Green et al. (2020). have indicated that the power transfer rate of solar PV in the market is mainly between 10 and 28%.

Solar panels are welcomed as an external energy system that can be linked to existing buildings and systems, but there is a systematic problem about time. Solar power is generated when the sun rises, but the peak power consumption for residential households is mainly at night. At the same time, winter has weaker solar irradiance, but places in

colder weather will consume more energy for heating (Aelenei & Gonçalves, 2014; Reis et al., 2019). The issue of the unbalanced energy supplement can be solved by connecting to the power grid to share the responsibility for power generation between traditional power plants and the renewable system, or installing battery storage for the solar power system. The former method, which could become part of an integrated grid system, reduces the dependency on traditional power resources and shares the renewable resource in the daytime or even contributes to a monthly or annual balance (Hasan & Mohamed, 2015; Hernandez & Kenny, 2010; Kumar, 2017; Liu et al., 2019; Reis et al., 2019; Tiwari et al., 2011), whereas the latter can build up an independent self-sufficient system through battery charging (Bendato et al., 2018; Luthander et al., 2016; Reis et al., 2019), though the cost of the battery is high and with lower efficiency (Merei et al., 2016).

As a self-sufficient solar power system, the percentage of power covered varies Luthander et al. (2015). reviewed related studies and indicated that the self-sufficiency rate without a storage system could reach 15 to 56%, depending on local factors for each case study. When it concerned energy storage or other ways to apply renewable energy without economic restrictions, the self-sufficiency rate can reach 70% (Luthander et al., 2015) or even 100% (Arcos-Vargas et al., 2019). As concerns the building type, residential dwellings and small shops can more easily reach a higher self-sufficiency rate due to their lower energy consumption compared with industry or business developments (Reis et al., 2019). Meanwhile, buildings lower than 10 metres or 3 storeys are able to generate more power than demand (Santos et al., 2014), and a single-family building of about 3–5 storeys has the potential to break even (Liu et al., 2019). While shorter buildings can more easily reach energy breakeven, they are also more easily shaded by taller buildings. The city pattern contributes a varying shadow distribution, and this impairs the solar energy performance (Amado & Poggi, 2012; Kumar, 2017; Mohajeri et al., 2016; Santos et al., 2014; Savvides et al., 2019). The shadow effect is one of the key issues when discussing the solar energy generation factor in cities (Amado & Poggi, 2012; Hong et al., 2017; Ko et al., 2015; Nguyen & Pearce, 2012; Redweik et al., 2013). However, when evaluating the self-sufficiency rate of renewable energy, most of the references do not mention the impact of the shadow effect, and this might reduce the trustworthiness of their findings for individual households.

This research aims to clarify how shadow covering affects the power generation on buildings of different heights, even though short and single-family residential dwellings might still be self-sufficient. The objective of this paper is to evaluate how the energy self-sufficiency rate of solar photovoltaic systems is affected by the surrounding building environment and to simulate it using a high-fidelity 3D building model. Two targets will be reached in this research: the impact of shadow covering on different heights of buildings and the accurate evaluation of the energy self-sufficiency rate based on a high-fidelity 3D building model.

2. Building model and methodology

The 3D building model is one of the most common media to use for solar energy simulation and there are several programmes available (Koutra et al., 2018). Although it is well-developed in the evaluation of city solar panels and used with sustainability as the core value, it has also been applied in several aspects of city development. Solar energy simulation with a 3D model always starts by evaluating the power potential through calculating the solar irradiance (Alrwashdeh et al., 2018; Azoumah et al., 2010) or the receiving area, including the rooftop (Chatzipoulka et al., 2016; Hong et al., 2017; Ko et al., 2015; Saadaoui et al., 2019), façade (Lobaccaro et al., 2012; Redweik et al., 2013), surface (Hernandez et al., 2014), or farmland (Amaducci et al., 2018; Malu et al., 2017), to improve the 3D model by formatting the tilt of the panels (Biljecki et al., 2015; Santos et al., 2014; Willenborg et al., 2018; Yuan et al., 2016). To reach higher power generation efficiency, many

researchers tend to pursue the optimal angle for higher production; therefore, solar tracking panels are commonly applied (Afrin et al., 2013; Benghanem, 2011; Hammad et al., 2017; Jacobson & Jadhav, 2018; Lave & Kleissl, 2011; Romero Rodríguez et al., 2017; Singh & Banerjee, 2016). Studies have pointed out the importance of city solar energy by the 3D building model from the perspective of energy potential (Amado & Poggi, 2012; Chatzipoulka et al., 2016; Mohajeri et al., 2016; Saadaoui et al., 2019), but it is rarer for them to link it to the idea of nZEB or even self-sufficiency, except for those who focus on city rebuilding or regeneration (Natanian & Auer, 2020). Therefore, this research will try to use the well-formatted LOD2 (Level of Detail) building model as the object to simulate the impact of the shadow effect on buildings of different heights from the perspective of the power self-sufficiency rate. Two steps will be applied in this research: extracting the LOD2 building model and evaluating the energy self-sufficiency rate by calculating the solar radiation on the surface of the building model. The procedure is illustrated in Fig. 1.

2.1. Building model extraction

This research was developed based on the LOD2 model. LOD is the building style defined by City GML (Geography Markup Language) ranging from LOD0 to LOD4 (Gröger et al., 2012). LOD1 and LOD2 are widely applied for the simulation of solar power potential. LOD1 is a model with no building shape but a cuboid. The building height might be presumed as 3 meters times the number of floors or by taking the highest point of the building and reshaping it as a flat rooftop (Biljecki et al., 2015; Ko et al., 2015). In the other approach, LOD2 presents the actual building height with the real building shape. Thus, it will be accurate when simulating the solar energy generation with consideration of the rooftop shape, slope, aspect and shadow effect (Willenborg et al., 2018) Fig. 2. shows the comparison between these two building models.

ESRI ArcMap is the application for calculation, and all of the building

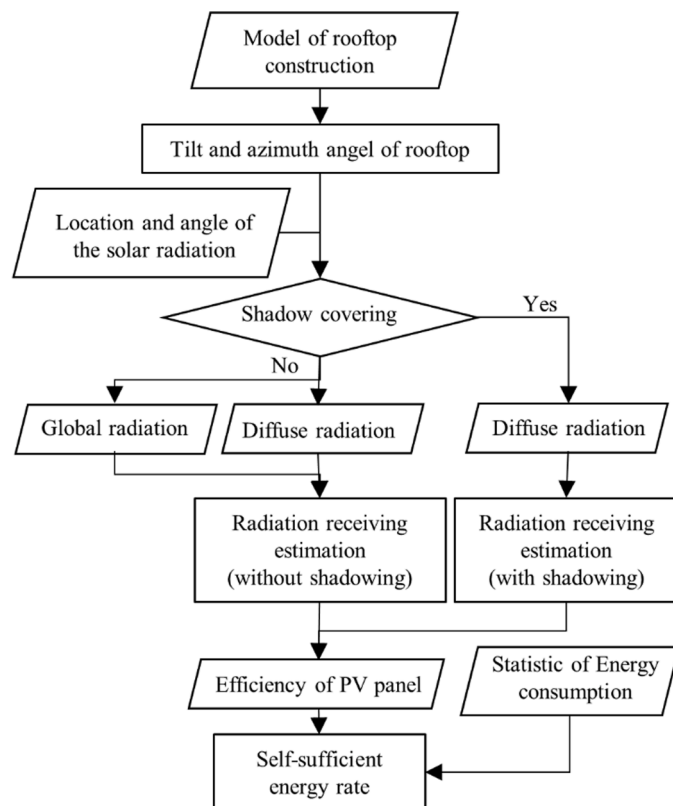


Fig. 1. The flowchart of proposed approach for PV power self-sufficient rate estimation.

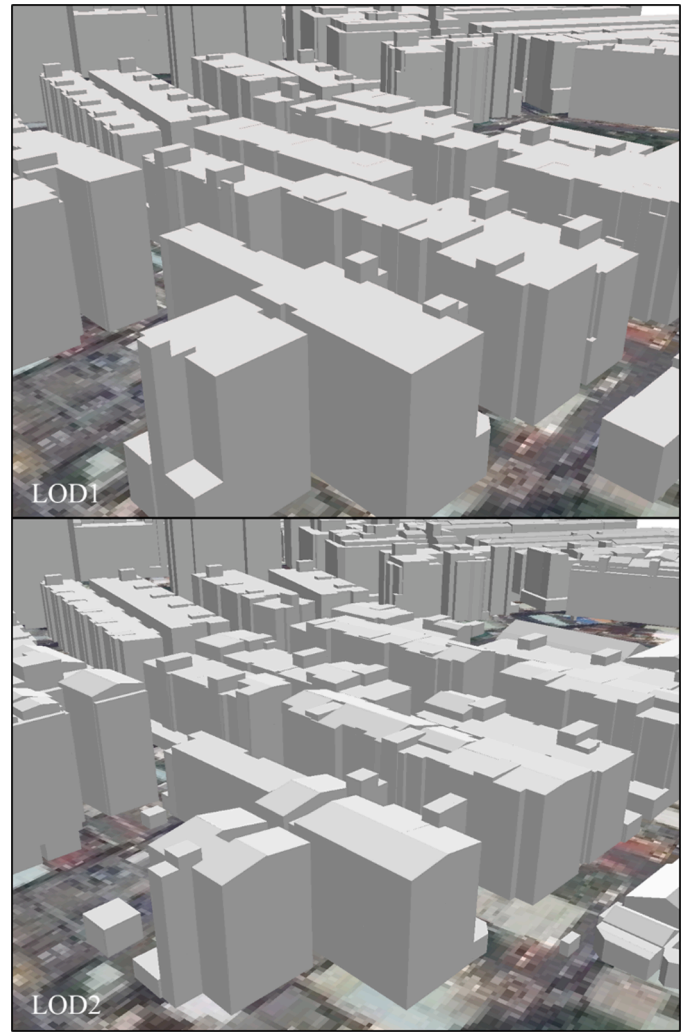


Fig. 2. The comparison between LOD1 and LOD2 building models.

data in this research will be transferred as mesh data with a 1 m^2 grid scale. The slope and the aspect of the rooftops will be calculated in each grid by the 3D Analyst Tool of ESRI ArcMap based on the height of the surrounding grid (see Fig. 3 and Eqs. (1) to (4)). Meanwhile, the edge of the rooftops is excluded for 1 metre using the Canny algorithm (Canny, 1986), considering the unfeasibility of the parapet area (see Fig. 4). To simplify the simulation, all of the rooftops with potential for panels are assumed to install solar PV panels by following their slope and orientation. Meanwhile, based on BrightstarSolar (2014), the common size of solar panel for residential rooftops is about $65 \times 39 \text{ in}^2$, or $165 \times 99 \text{ cm}^2$, and its installed capacity will be between 230 and 275 W. This research assumed that the installed capacity of the equipment is 250 W and the installation of 1 kW capacity will occupy about 6.5 m^2 (or the installed

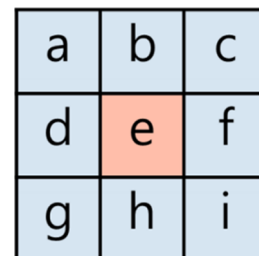


Fig. 3. The illustration of calculating the slope and aspect.

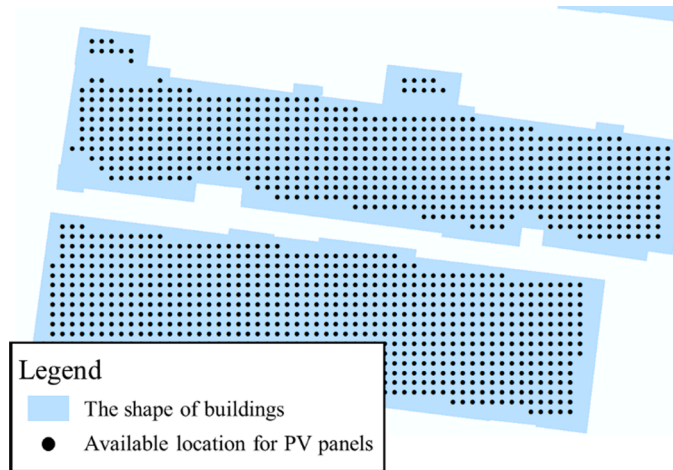


Fig. 4. The example of feasible area for solar panels by applying Canny algorithm.

capacity will be about 150 W per m²).

$$dy/dx = [(c + 2f + i) - (a + 2d + g)] / (8 \times \text{cellsize}) \quad (1)$$

$$dz/dy = [(g + 2h + i) - (a + 2b + c)] / (8 \times \text{cellsize}) \quad (2)$$

Eqs. (1) and (2) represent the connection between the x, y, and z axes. *a* to *i* represent the height of each grid. The slope and aspect degree can therefore be derived by using Eq. (3) and (4).

$$\text{Slope} = \tan^{-1} \left(\sqrt{(dz/dx)^2 + (dz/dy)^2} \right) \times (180 / \pi) \quad (3)$$

$$\text{Aspect} = \tan^{-1} [(dz/dy) / -(dz/dx)] \times (180 / \pi) \quad (4)$$

To understand the impact of shadow covering, this research established two scenarios to simulate the building, with and without considering the surrounding construction. Scenario A is analysed in the form of a single building, whereas Scenario B considers the whole area (see Fig. 5 as an example). The solar radiation calculated in Scenario A is in an ideal condition where there is no impact of the surroundings that decreases the received radiation. The solar radiation in Scenario B is closer to the reality. In another sense, in an area with the same solar radiation, the result of Scenario A can also represent the average condition of an isolated building, whereas Scenario B shows the general situation in random surroundings. The results of the two scenarios are then classified into 16 groups according to the number of storeys in order to determine the level of the shadow effect on buildings of different heights.

2.2. Self-sufficiency evaluation

TMY (Typical Meteorological Year)3 data is long-term, mainly over 10 years, hourly collected data on weather conditions (Ho et al., 2013). Meteorologists can establish a general weather condition for the whole year by standardising all of the information. TMY data includes direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), global horizontal irradiance (GHI), and the solar azimuth angle, which will be applied as the solar input Eq. 5. shows the relation between GHI, DHI, and DNI. The solar incidence angle (θ) is calculated by the solar declination angle (δ), latitude (*L*), tilt inclination angle (β), tilt azimuth angle (z_s), and hour angle (*h*) as in Eq. 6.

$$GHI = DHI + DNI \times \cos\theta \quad (5)$$

$$\cos\theta = \sin\delta\sin L\cos\beta + \sin\delta\cos L\sin\beta\cos z_s + \cos\delta\cos L\cos\beta - \cos\delta\sin L\sin\beta\cos z_s \cosh - \cos\delta\sin\beta\sin z_s \sinh \quad (6)$$

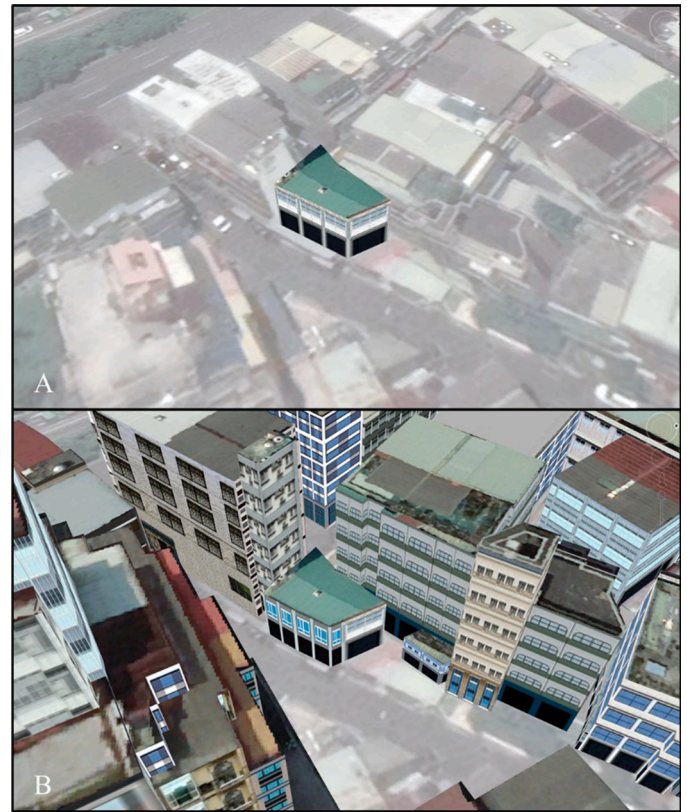


Fig. 5. An example of extracted single building (A) and the original pattern (B).

The solar irradiance received on the rooftop is DNI and DHI Perez et al.'s (1987). formula is input to calculate the amount of DNI and DHI Eq. (7.) shows the Perez formula, where I_t is the global radiation casting on the rooftop; $I_{b,N}$ is the global radiation; $I_{d,h}$ is the diffuse radiation; F_1 and F_2 are complex empirically fitted functions representing the surrounding conditions, which are the circumsolar and horizon brightness, $a = \max(0, \cos\theta)$ and $b = \max(\cos 85^\circ, \cos\Phi)$ (Φ is the solar zenith angle).

$$I_t = I_{b,N} \times \cos\theta + I_{d,h} \times [(1 - F_1)[(1 + \cos\beta) / 2] + F_1(a / b) + F_2\sin\beta] \quad (7)$$

Due to the shortage of data on the circumsolar and horizon brightness indexes and their limited impact, Eq. (7) can be simplified as Eq. (8).

$$I_t = I_{b,N} \times \cos\theta + I_{d,h} \times [(1 + \cos\beta) / 2] \quad (8)$$

From Eq. 3, the ideal solar irradiance received on the tilted rooftop can be estimated, and the shadow effect is calculated by Hillshade analysis in ESRI ArcGIS. In Hillshade, the shadow effect is presented in a grey scale with 255 labels, from 0 to 254. 0 indicates the 100% covered condition without any solar casting, whereas 254 indicates that the area receives all of the possible solar radiation.

With the confirmation of the received solar radiation on the individual grid of the rooftop, Eq. (9) is applied to transform the solar radiation into power. In Eq. (9), P is the power that this research will infer; η , I , and A are the transfer rate of power efficiency, the received solar radiation, and the area of the PV panel, respectively. Although η in the recent study has been proved to be able to reach 28%, this efficiency comes from the lab in a constant condition (Green et al., 2020). In the real scenario, temperature shows an adverse impact on generating efficiency (Jakubiec & Reinhart, 2013). Instead, 15% is the commonly assumed number due to the popular marketing application (Brito et al., 2012; Kanter & Davidsson, 2014; Kouhestani et al., 2019) and the simulation result in the same area pointed out that 15% is close to the official result (Han et al., 2022). Hence, 15% would be adopted as the η

in this research.

$$P = \eta \times I \times A \quad (9)$$

To calculate the self-sufficiency rate of renewable energy in the view of nZEB, Sartori et al. (2010) formulated one of the most common methods Eq. (10.) to (12) shows the balance of the delivered and feed-in energy, and crediting system in these equations standardises the unit whereas i means various energy carrier. The time period it covers may vary depending on the data condition and the demand of the analysis, but a monthly frame is common (D'Agostino et al., 2016; Kumar, 2017; Liu et al., 2019). Because the renewable energy supply in this research only focuses on solar energy generation, it becomes the only factor as the feed-in energy. To transfer the self-sufficiency into percentage, this research transforms Eq. (12) into Eq. (13). When the value exceeds 100%, the analysing target in this time period will be considered as a nZEB.

$$import = \sum_i \text{delivered energy}(i) \times \text{credits}(i) \quad (10)$$

$$export = \sum_i \text{feed-in energy}(i) \times \text{credits}(i) \quad (11)$$

$$nZEB = |export| - |import| \geq 0 \quad (12)$$

$$\text{Self-sufficiency rate} = export/import \times 100\% \quad (13)$$

3. Result

3.1. Case study area

The south part of Shezi in Taipei City, Taiwan is the case study area of this research (Fig. 6). It is a shoal in the Tamsui River, and it is therefore isolated from surrounding development. The isolated environment is helpful for excluding the shadow effect resulting from surrounding buildings. This shoal comprises north and south parts. Due to

the risk of flooding, the north part of Shezi was not allowed to follow the zoning plan for construction and had only some organic development before the restriction (Taipei City Gov., 2011; Yang, 2003). This research therefore focused on the south part, where the pattern is composed of various buildings with between 1 and 16 floors. The building composition in percentage is shown in Fig. 7. It indicates that buildings of 3 or 4 floors are the majority, and buildings lower than 3 storeys are high account for almost half the total. With the characteristic of highly residential-commercial mixed development and low commercial activity, this research focused on the area excluding every non-commercial and residential use space and assumed that all of the area is in the power consumption of the single-family type.

The TMY3 data collected by Taipei meteorological stations is used to

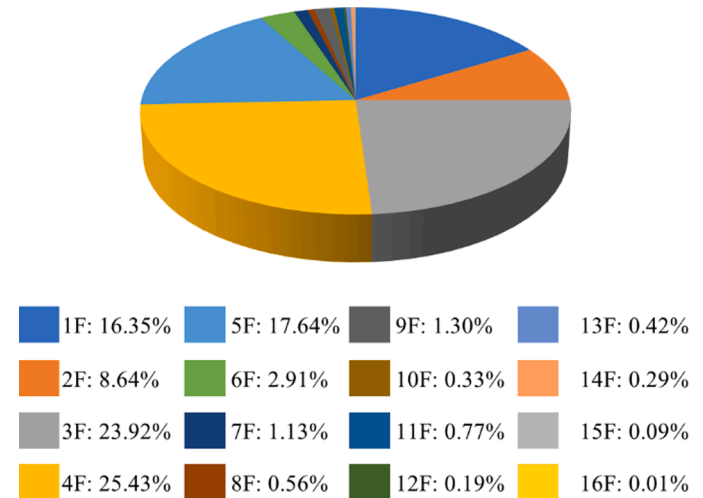


Fig. 7. The composition of building in the case study area with the classification of building storey.

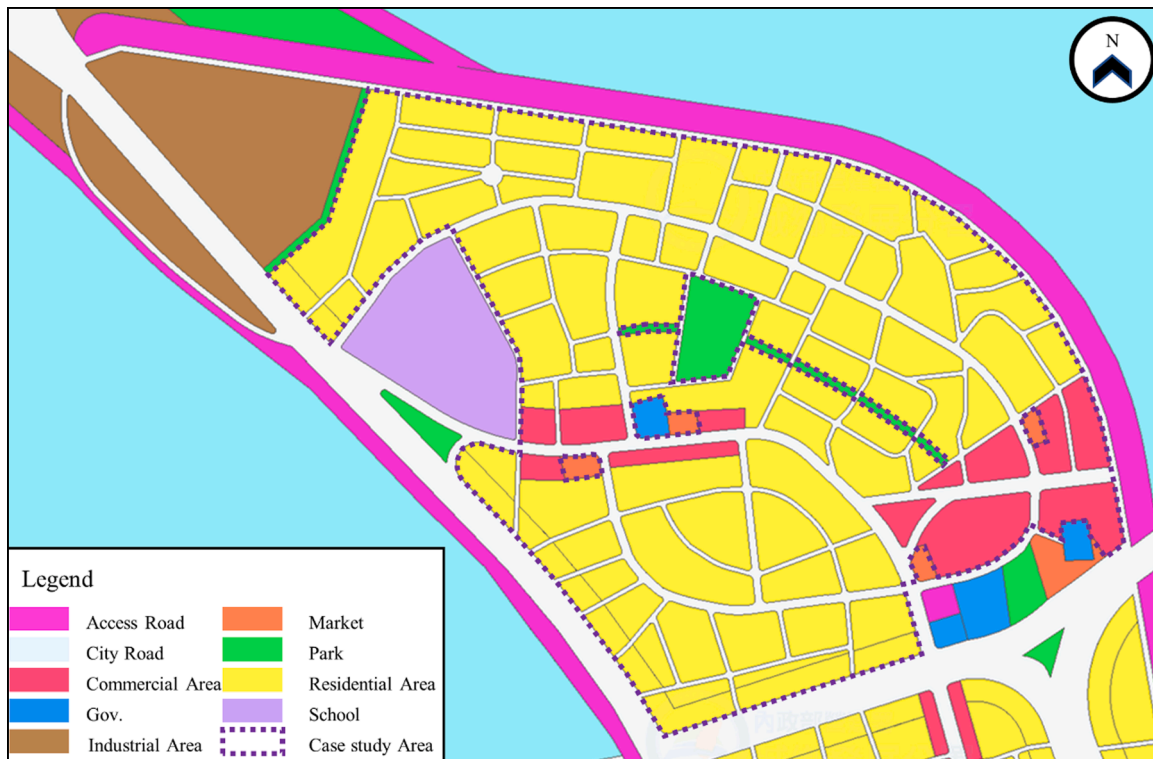


Fig. 6. The location and the zoning map of case study area.

represent the solar condition in this research Fig. 8. indicates the composition of GHI in TMY3 Taipei. It shows that, compared with DNI, it is DHI that provides about two-thirds of the radiation to the surface. Thus, areas that are always covered by shadow still have strong potential to generate energy based on the support of DHI. This indicates that shadow covering is not a factor that excludes the rooftop area for installing solar panels.

Fig. 9 illustrates the average power consumption of a single-family building during the last 12 months (Taiwan Power Company, 2021). The peak energy dependency occurs in September 2020, and the lowest is in December 2020. Summer is the season with the highest energy consumption and highest solar irradiance, and winter is in the opposite condition. Therefore, the trend of energy demand does not have to deal with the same circumstance that Aelenei and Gonçalves (2014) and Reis et al. (2019) confronted about higher energy consumption during winter due to the dependency of heaters. Meanwhile, according to the annual statistical data from the DGBAS (Directorate General of Budget, Accounting and Statistics, Administrative Yuan, Taiwan, 2020), the average area of a single-family home in Taiwan in 2019 is 45.1 ping (or pyeong in Korea, tsubo in Japan), which is close to 149.1 m². The evaluation of energy self-sufficiency in this research thus assumes that the area of a single-family house is 149.1 m², and Fig. 9 shows the monthly energy consumption.

3.2. Potential solar generation

In the whole case study area, the potential energy generation from the solar irradiance reaches about 94.63 and 92.04 kWh yearly per m² rooftop in Scenarios A and B, respectively. It is clear that the gap in the yearly result between the two scenarios is small. The monthly distribution of energy generation per rooftop area in both scenarios is illustrated in Fig. 10, which shows that the highest energy generation occurs in July and the lowest is in January. The former can reach 13.18 and 12.89 kWh in the two scenarios, whereas the latter only achieves 4.12 and 3.95 kWh. From comparison of the two scenarios, the difference resulting from the shadow effect is not obvious. The biggest gap is seen in December, with 4.7% error, and the smallest one is in June, with only 1.09% difference. However, when categorising buildings by their number of storeys, the impact of the shadow effect can be discovered

Fig. 11. illustrates the impact of the shadow effect in building groups with different storeys, and the correlation, including RMSE (Root Mean Square Error), MAE (Mean Squared Error), R, and R², between the two scenarios is listed in Table 1. The shadow effect has an important role in winter due to the lower solar incidence angle, and the impact is relatively weak in summer. Buildings of 1 storey suffer the most serious shadow impact, ranging from 4.34% to 18.33%, whereas 15- and 16-storey buildings are always 0% because there are no higher buildings surrounding them. Apart from 1-storey buildings, those with 2, 9, and 11 storeys were also subject to a relatively higher influence from surrounding shadow Table 1. presents some more precise information. Because RMSE and MAE are based on the rooftop energy potential between 2 scenarios, the higher value in these two indexes means the wider range of shadow effect in each group. There would be no doubt that buildings in 1 or 2 storeys suffered more serious shadow effects, but 9 and 11 storeys groups share the similar trend. It means that buildings might be grouped in two types: tall and short buildings. The tall buildings are clustered and surrounded by short ones. Buildings in 10 storeys has weaker shadow covering compared with that in 9 and 11 storeys. It might because 10-storey buildings are mainly encircled by shorter buildings.

3.3. Evaluation of self-sufficiency rate

Solar panels in the rooftop area were reported as having a very high output per m² in the previous section, but their generation might not be able to cover the demand of the construction beneath, depending on the number of storeys Fig. 12. shows the variation of the energy self-sufficiency rate in different building groups as well as the average distribution for both scenarios. It indicates that the decreasing of the self-sufficiency rate and the storey number show a very strong correlation, with R² of 0.9504 and 0.9572 for Scenarios A and B, respectively. Due to the close connection between the rooftop area and the total floor area, the impact of the Canny algorithm is weak. Meanwhile, the shadow effect is the only factor that differentiates these two scenarios. The gap of only 0.0068 in the R² between them shows that although the shadow effect is weak for decreasing the generation, it strengthens the correlation between the self-sufficiency rate and the floor area served.

According to the information in Fig. 11, although there is a shadow

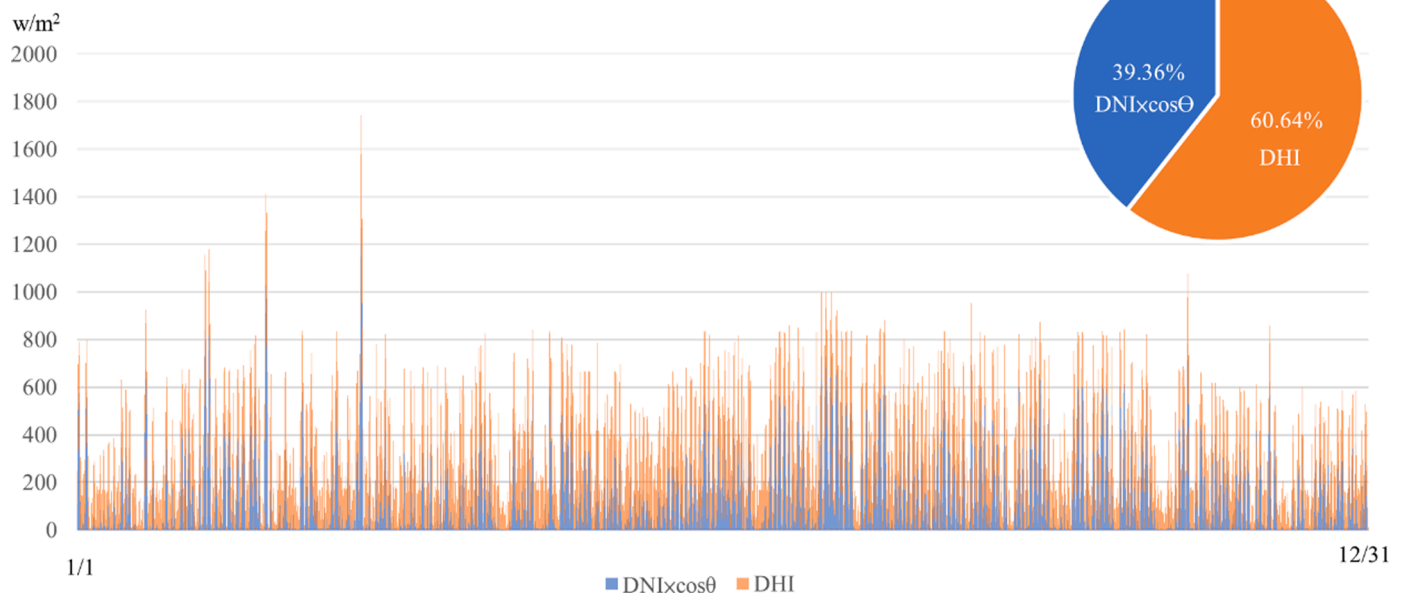


Fig. 8. The distribution of the solar irradiance on surface in TMY3 Taipei data.

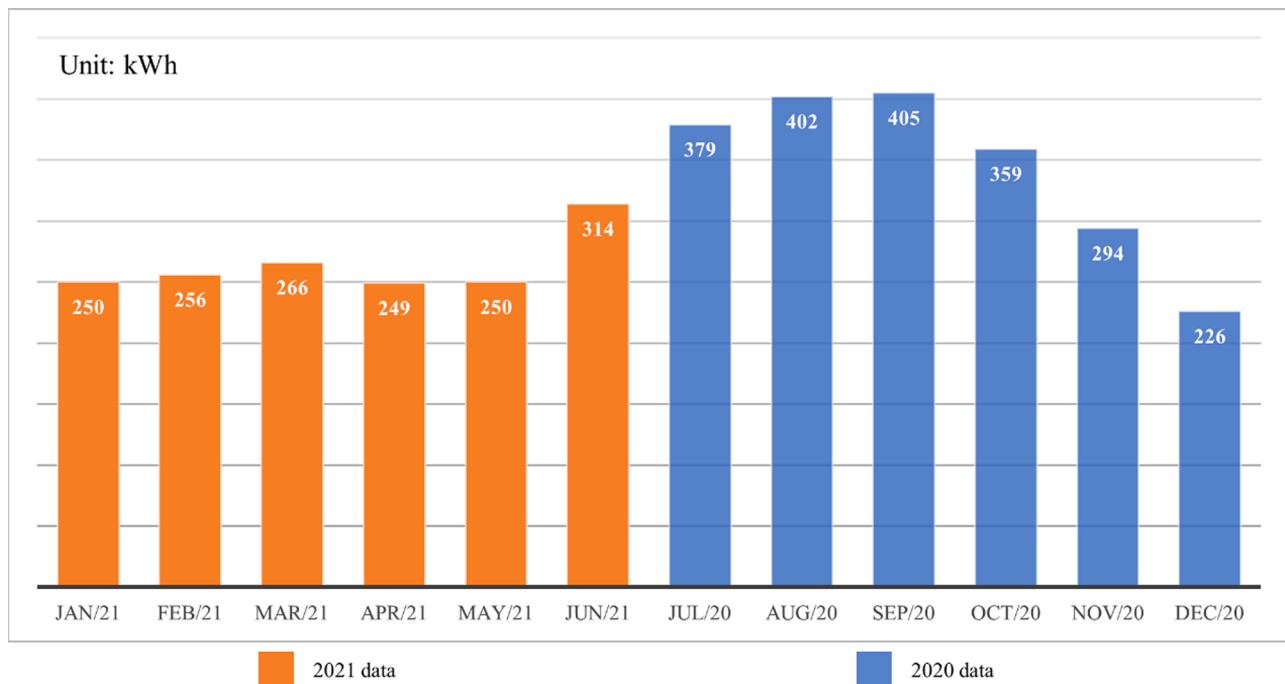


Fig. 9. Average power consumption per single-family unit per month in 2020/2021.

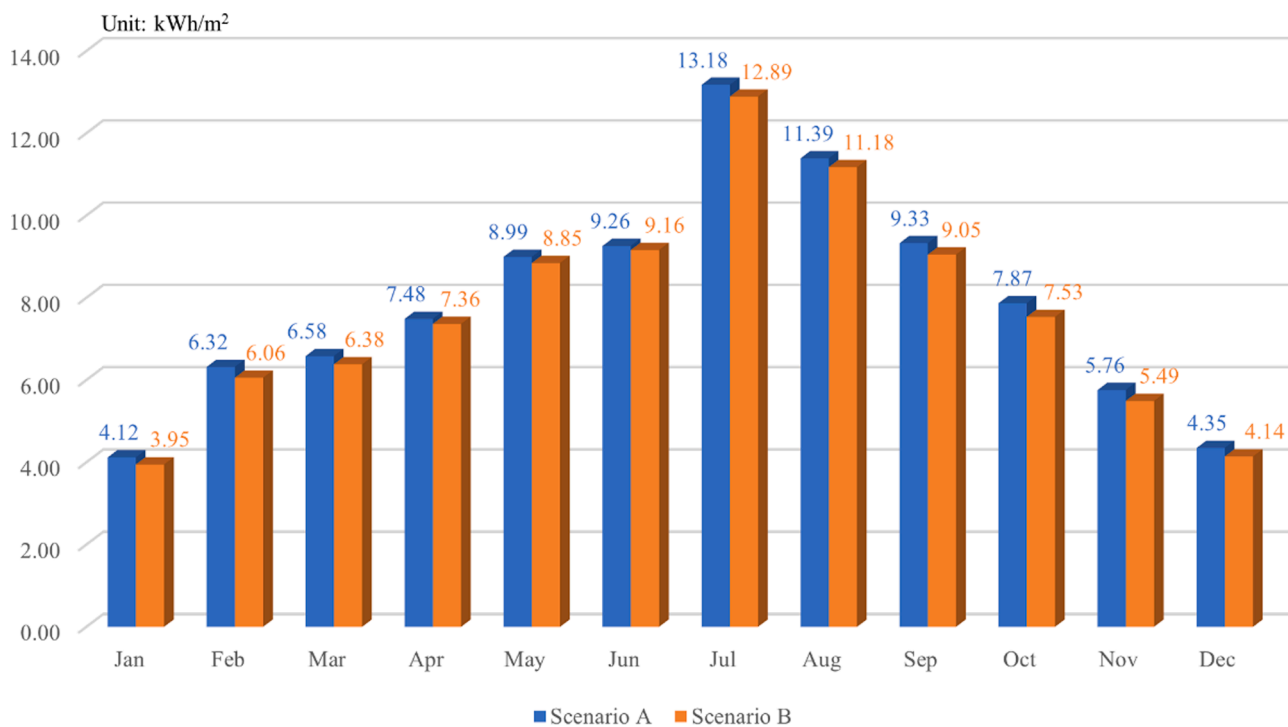


Fig. 10. The monthly distribution of the potential solar generation per m² rooftop in the whole case study area.

effect between these two scenarios, the impact in most of the groups is rare. The shadow effect in buildings in the more than 2-storey groups have only about a 1% energy decrease. It has a great impact on the 1- and 2-storey buildings, but the high self-sufficiency rate in these groups means that their support system is fully maintained Table 2. indicates the variation of these two scenarios in every storey group, as well as the whole area data. In general, buildings of less than 5 storeys will receive sufficient solar radiation to support their daily energy consumption individually in the scope of yearly distribution. The percentage of

decreasing energy self-sufficiency rate can reach 5 to 10% in some groups. For the condition of the whole area, the solar radiation in both scenarios can provide a sufficient energy supply, achieving 106.72 and 103.80% of energy demand, respectively. With this sufficient self-supported renewable solar energy system, demand from the traditional power grid is not necessary in view of the solar energy self-sufficiency rate of over 100%. However, although the total energy generation can cover the demand, it should be noted that the calculation is based on the yearly data.

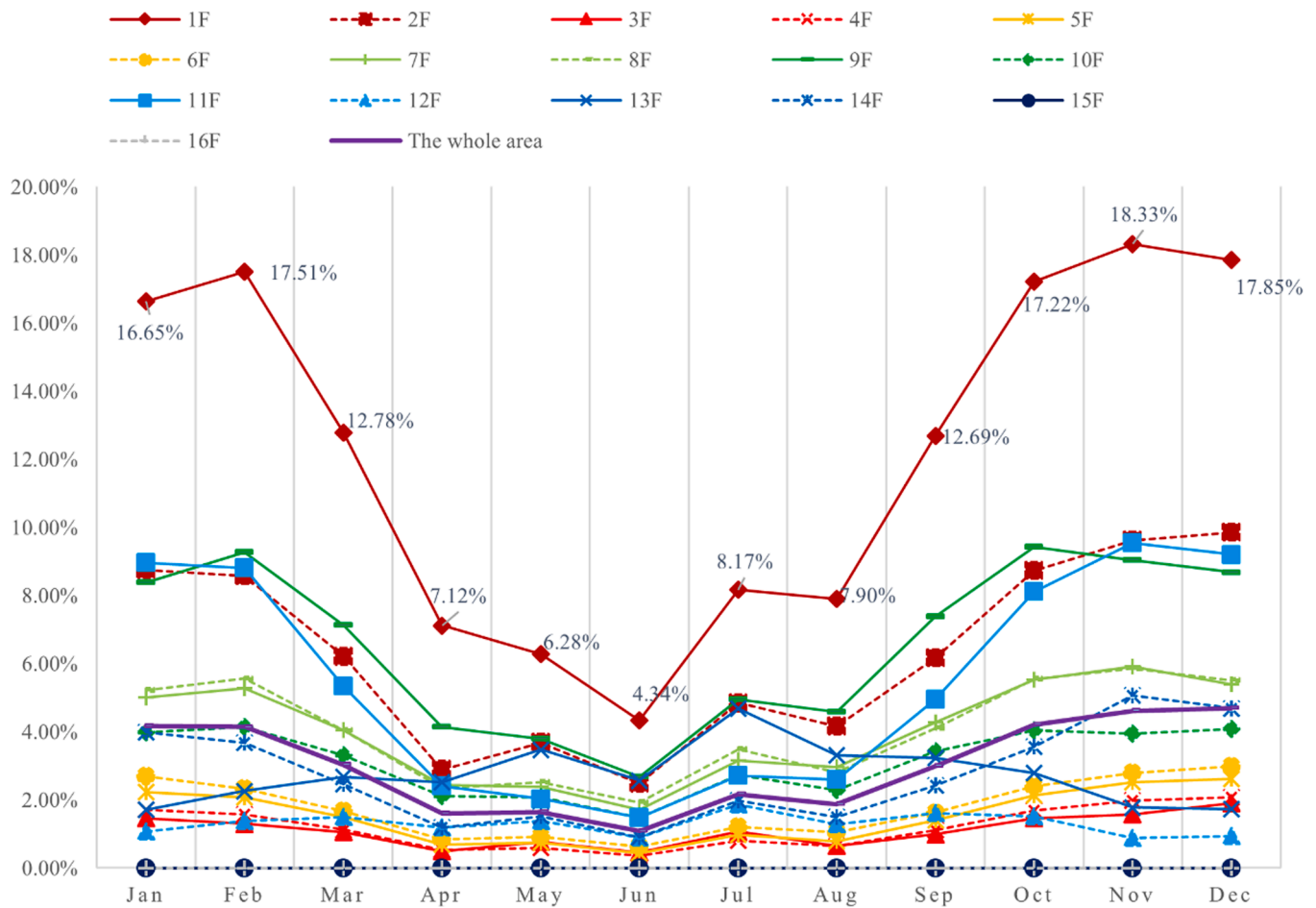


Fig. 11. The percentage energy loss resulted from shadow effect.

Table 1
Statistics for error of Scenario A and B.

Group	RMSE	MAE	R	R ²
1F	7.5121	4.9356	0.9917	0.9835
2F	5.8388	3.9137	0.9944	0.9888
3F	2.2340	1.1593	0.9992	0.9985
4F	2.1968	0.9554	0.9992	0.9984
5F	3.6420	1.6759	0.9980	0.9959
6F	2.2081	1.0001	0.9992	0.9983
7F	3.0824	1.4059	0.9982	0.9964
8F	2.7628	1.6756	0.9986	0.9972
9F	3.7226	2.5209	0.9978	0.9957
10F	3.3203	1.8221	0.9943	0.9886
11F	5.0378	3.5038	0.9959	0.9918
12F	2.5836	1.0677	0.9942	0.9884
13F	1.8628	1.0249	0.9979	0.9959
14F	1.0897	0.5687	0.9999	0.9999
15F	0.0000	0.0000	1.0000	1.0000
16F	0.0000	0.0000	-	-
Whole Area	5.1022	2.7196	0.9958	0.9915

Tables 3 and 4 list the energy self-sufficiency rate in Scenarios A and B in the scale of monthly and yearly distribution, as illustrated also in Figs. 13 and 14. Rates which are more than 100% are highlighted in bold. It turns out that in the perspective of the monthly energy self-sufficiency rate, the energy consumption can only be covered from April to August in both scenarios in the whole area. When there is no surrounding shadow effect, the period when the energy demand can be covered can be extended to half of the year starting from late winter. In the classification of building storeys, the fully self-sufficient months in

both scenarios are the same and buildings lower than 3 storeys achieve not only yearly but also monthly full energy support. This means that in the summer time, the energy generation of lower storey building groups can satisfy the shortfall of taller ones if the solar energy system is designed by linking all of the rooftops in this area as a local grid. Hence, if the whole area shares the same power grid for solar renewable energy, the monthly energy self-sufficiency rate could reach from 65% to 146% in Scenario B. As concerns the yearly energy self-sufficiency rate, it could reach about 104%; that is, there would be a paper profit in energy generation by applying solar panels in the whole area. Reaching full energy self-sufficiency is based on the composition of the area. Buildings with fewer storey(s) are key groups to sponsor the solar energy. This also indicates that the solar energy system can achieve better performance in a relatively low-density city pattern. An integrated solar power grid can partially cover higher buildings, as the case study shows that buildings with sufficient surplus energy can meet some of the demand of those with more storeys. Based on Table 4, a 1-storey building could cover 235% of its energy demand annually, and a 16-storey one could cover that of a 16-storey area for 13% Table 5. indicates the additional energy demand for building groups that cannot reach energy self-sufficiency. Taking the 5-storey building group as an example, the energy shortage for every 1 kWhm² of this group could be covered by 0.65 kWhm², 1.28 kWhm², 2 kWhm², and 12.74 kWhm² of the 1-, 2-, 3-, and 4-storey groups, respectively. For the tallest building in this area, when there is 10.33 kWhm² of a 1-storey building, the energy demand of 1 kWhm² of the 16-storey building could be covered.

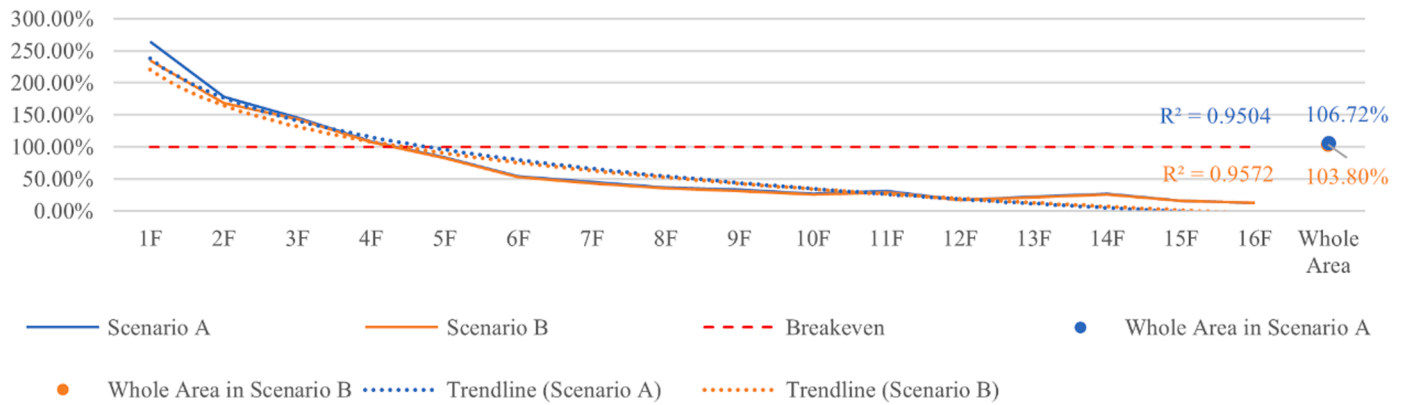


Fig. 12. The varying energy self-sufficient rate in different storey of building groups.

Table 2

The variation of self-sufficiency rate and the shadow impact in different storey groups.

Group	Scenario A	Scenario B	Variation	By %
1F	264.01%	234.78%	-29.24%	-11.07%
2F	178.13%	167.87%	-10.25%	-5.76%
3F	144.95%	143.49%	-1.46%	-1.01%
4F	107.96%	106.83%	-1.13%	-1.05%
5F	83.71%	82.60%	-1.11%	-1.33%
6F	53.46%	52.63%	-0.84%	-1.57%
7F	45.20%	43.52%	-1.68%	-3.72%
8F	36.93%	35.53%	-1.40%	-3.80%
9F	33.00%	30.98%	-2.02%	-6.13%
10F	26.87%	26.08%	-0.79%	-2.95%
11F	30.90%	29.43%	-1.46%	-4.74%
12F	16.81%	16.58%	-0.23%	-1.35%
13F	22.30%	21.63%	-0.67%	-2.98%
14F	26.44%	25.79%	-0.64%	-2.43%
15F	15.59%	15.59%	-0.00%	0.00%
16F	13.01%	13.01%	-0.00%	0.00%
Whole Area	106.72%	103.80%	-2.91%	-2.73%

4. Discussion

This research started from the comparison of the solar potential in both scenarios, distinguished based on the shadow effect from the surroundings. It indicated that the shadow effect from surroundings is not strong in buildings over 2 storeys. Although shadow decreased the energy potential of shorter buildings, the net energy generation was high and mainly reached double of the energy demand. By contrast, higher buildings suffered less shadow effect except that in 9 and 11 storeys, but

all of their energy consumption started to exceed the quota of potential energy generation once they reached 4 storeys on average. To achieve the target of self-sufficient development in the presumed energy transfer rate as 15%, the energy self-sufficiency system could work in combination, letting the extra energy generation from rooftops on shorter buildings cover the consumption in higher ones. Taller buildings in some storeys suffer more serious energy generating reduction, it would be improved when the city pattern has a proper design or arrangement. The evaluation of the monthly and yearly self-sufficiency rate found that in 15% energy transfer rate, some building groups as well as the whole area can reach a condition of perfect self-sufficiency, but the smallest scale of energy consumption is monthly data, and this cannot reflect the instant energy demand. This general shortage is possible to get improved by the innovation of solar photovoltaic with higher energy transfer rate, though the generating period is still limited. There is no solar energy output during the night time, but the energy consumption will be consistent. Thus, while the potential energy generation from the rooftop solar PV system can cover the demand in the whole area, it cannot reflect the trends of demand and supply at any given instant. To put this theoretical self-sufficiency rate into practice, importing an energy storage system or building an energy-sharing grid system with the existing power grid are popular approaches. The former can store the extra energy in the on-peak solar hours and use it during off-peak hours in the system, whereas in the latter approach, the output of the solar PV system can cover the energy demand outside the area via the grid system during on-peak hours, thus reducing the dependency on traditional power plants and receiving energy from those plants through the grid net as replenishment. These two approaches can enable a good energy management arrangement, while the cost as well as the suitability of the

Table 3

The distribution of energy self-sufficient rate in the scenario A (unit: %).

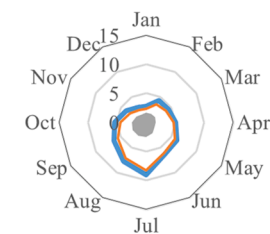
MonthStorey(s)	Storey(s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Whole Year
1		168	251	252	306	366	300	354	289	235	223	199	196	264
2		113	169	170	207	247	203	239	195	158	150	135	132	178
3		92	138	138	168	201	165	194	158	129	123	110	108	145
4		69	103	103	125	150	123	145	118	96	91	82	80	108
5		53	80	80	97	116	95	112	91	74	71	63	62	84
6		34	51	51	62	74	61	72	58	47	45	40	40	53
7		29	43	43	52	63	52	61	49	40	38	34	34	45
8		24	35	35	43	51	42	49	40	33	31	28	27	37
9		21	31	31	38	46	38	44	36	29	28	25	24	33
10		17	26	26	31	37	31	36	29	24	23	20	20	27
11		20	29	29	36	43	35	41	34	27	26	23	23	31
12		11	16	16	20	23	19	23	18	15	14	13	12	17
13		14	21	21	26	31	25	30	24	20	19	17	17	22
14		17	25	25	31	37	30	35	29	23	22	20	20	26
15		10	15	15	18	22	18	21	17	14	13	12	12	16
16		8	12	12	15	18	15	17	14	12	11	10	10	13
All		68	102	102	124	148	121	143	117	95	90	81	79	107

Table 4

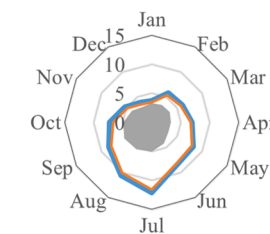
The distribution of energy self-sufficient rate in the scenario B (unit: %).

Month Storey(s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Whole Year
1	140	207	220	284	343	287	325	266	205	185	163	161	235
2	103	155	159	201	238	198	227	187	148	137	122	119	168
3	91	136	137	167	200	164	192	157	128	121	108	106	143
4	67	101	102	125	149	122	144	117	95	90	80	78	107
5	52	78	79	96	115	95	111	91	73	69	62	60	83
6	33	50	50	62	74	61	71	58	47	44	39	38	53
7	27	41	41	51	61	51	59	48	38	36	32	32	44
8	22	33	34	42	50	41	48	39	31	30	26	26	36
9	19	28	29	37	44	37	42	34	27	25	23	22	31
10	16	24	25	31	37	30	35	29	23	22	19	19	26
11	18	27	28	35	42	35	40	33	26	24	21	21	29
12	11	16	16	19	23	19	22	18	15	14	13	12	17
13	14	21	21	25	30	25	29	24	19	18	17	16	22
14	16	24	25	30	36	30	35	28	23	22	19	19	26
15	10	15	15	18	22	18	21	17	14	13	12	12	16
16	8	12	12	15	18	15	17	14	12	11	10	10	13
All	65	97	99	122	146	120	140	114	92	86	77	75	104

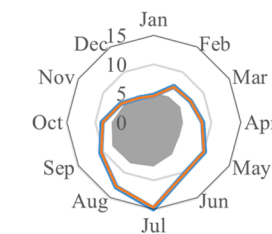
1-storey



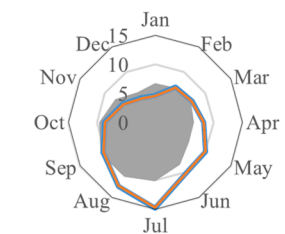
2-storey



3-storey



4-storey



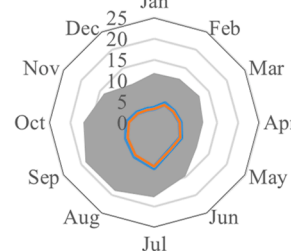
5-storey



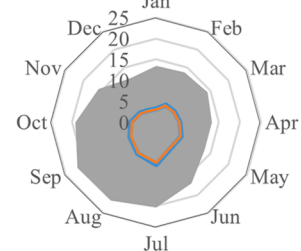
6-storey



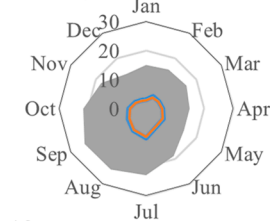
7-storey



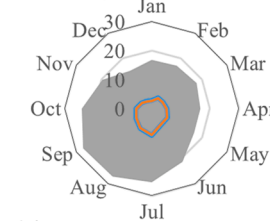
8-storey



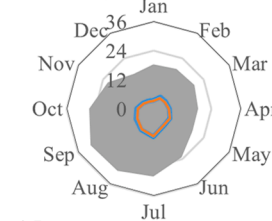
9-storey



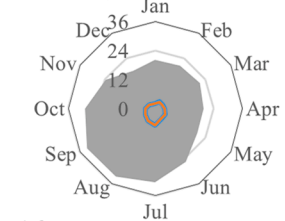
10-storey



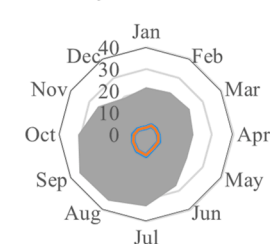
11-storey



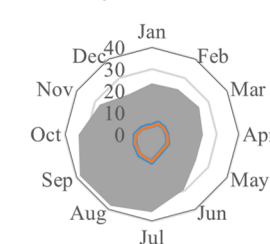
12-storey



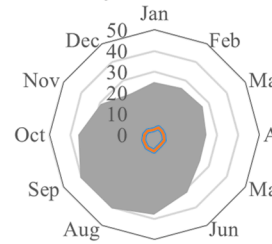
13-storey



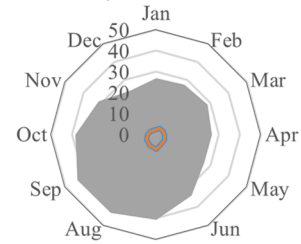
14-storey



15-storey



16-storey



■ Energy Consumption ■ Scenario A ■ Scenario B

Fig. 13. The self-energy covering monthly condition classified by storey groups.

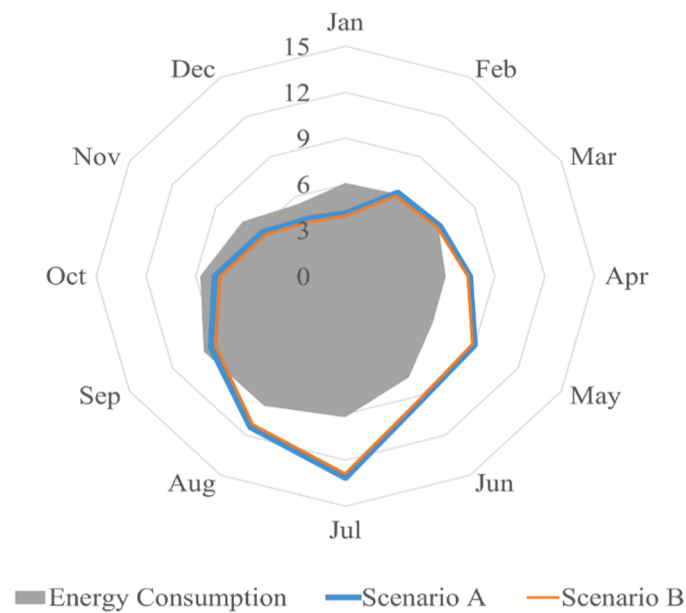


Fig. 14. The self-energy covering yearly condition classified by storey groups.

Table 5
Additional energy support from other building groups (unit: m²)

m ²	1F	2F	3F	4F
1F				
2F		Fully energy self-sufficient		
3F				
4F				
5F	0.65	1.28	2.00	12.74
6F	2.11	4.19	6.54	41.61
7F	2.93	5.83	9.09	57.89
8F	3.83	7.60	11.86	75.51
9F	4.61	9.15	14.28	90.95
10F	5.48	10.89	17.00	108.23
11F	5.76	11.44	17.85	113.66
12F	7.43	14.75	23.02	146.57
13F	7.56	15.01	23.43	149.17
14F	7.71	15.31	23.89	152.11
15F	8.77	17.41	27.17	173.02
16F	10.33	20.51	32.00	203.78

facilities, which might belong to the EE category, could be a subject for further development.

5. Conclusion

This research identifies the potential self-sufficiency rate under the shadow effect based on the application of a rooftop solar photovoltaic system in buildings of different heights in every possible area. It shows that, although shadows from taller buildings led to about 5 to 10% energy decrease on the shorter buildings in some city patterns. Overall, the effect of shadow cover on solar energy generation is limited. Shadow has an obvious impact on shorter building groups, but these are still the foundation of the whole energy self-sufficiency system due to their high net output. Compared with the results reviewed by Luthander et al. (2015) and (Arcos-Vargas et al., 2019), in the perspective of the energy self-sufficiency rate, the self-efficiency rate in this study area is higher under the energy transfer rate in 15%. This might be attributable to the sufficient solar radiation as well as the well-balanced building composition. That is, when the rooftop solar PV system is the only resource of renewable energy, an area with many skyscrapers should make a strategic urban development to arrange shorter buildings or space with proper quantity to be the foundation of solar energy support and

separate buildings by different height to decrease mutual shadow effect. In short, to achieve better energy self-sufficiency performance, a proper arrangement of building height and composition is necessary.

Meanwhile, the shorter buildings in the taller building groups suffered the similar shadowing condition as the shortest buildings. Different from the buildings in 1 or 2 storeys, they have not only bad self-sufficiency rate but also huge energy consumption. While taller buildings are inevitable in cities, the pattern among them should be evaluated to reduce the dependency on shorter buildings in the same area.

This paper shows the relation of energy supporting conditions in different groups of buildings, and it might serve as a basic guideline for the case study area, or in areas with a similar building distribution, as a city pattern model to the code of urban design. Meanwhile, the approach adopted in this paper can also be practised in any other place in order to pursue a balanced city development between skyscrapers and self-sufficient housings in the view of urban design for general energy self-sufficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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