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An integrated technical, economic, and environmental framework for evaluating the rooftop photovoltaic potential of old residential buildings

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ABSTRACT

Energy-saving reconstruction of old residential buildings is a vital way to achieve sustainable development, but the potential of rooftop photovoltaic (PV) energy-saving in old residential buildings has not been studied. This study established a basic framework for the estimation of rooftop PV technical, economic and environmental potential in the old residential buildings of Nanjing City, and provide the prediction results for the development of rooftop PV development plan in Nanjing. We estimated the available area, maximum electricity generation, environmental and economic benefits of rooftop PV in five districts of Nanjing by using building roof profile data, calculation method of maximum solar radiation at optimal tilt angle and GIS method. We find that the electricity generation potential of installing rooftop PV in the old residential buildings in the study area would meet about 17.7–20% of the residential electricity demand under three scenarios of the PV performance ratios (PR). Additionally, the carbon reduction potential of the life cycle rooftop PV reaches 13912874.12t (PR = 0.85), 13094469.76t (PR = 0.8), and 12276065.4t (PR = 0.75), respectively; and the result of economic potential shows that the life cycle of rooftop PV cannot generate economic benefits with an NPV value less than 0. The feasibility analysis framework provided in this paper can be applied to the assessment of rooftop PV potential in other cities in China, and provide valuable advice for the rational planning of rooftop PV.

1. Introduction

The energy consumption generated by the building sector accounts for a large proportion of the global total energy consumption (Asadi et al., 2012; Ma et al., 2012). Residential buildings in China before 2000 had few regulations for energy-saving standards. This resulted in a large amount of energy consumption and carbon emissions in the actual operation of these buildings (Ouyang et al., 2011). Moreover, from 2002 to 2010, the energy consumption of the existing residential building in China had risen sharply from 171.62 million tons of coal equivalent to 345.58 million tons, an increase of 101.36% (Nie and Kemp, 2014). In addition to an obvious increase in energy consumption, this also had a certain negative impact on the environment. Therefore, it is essential to reduce the existing building energy consumption by these old buildings in a timely manner using energy-saving renovations to cope with the potential energy challenges and environmental issues.

Studies have been conducted to develop and amplify different renovation methods to reduce energy consumption of the existing buildings (Casquero-Modrego and Goñi-Modrego, 2019; Liu et al., 2019; Xin et al., 2018; Zhou et al., 2018; Luddeni et al., 2018; Sarihi et al., 2021). The potential improvement strategies and measures proposed in the existing studies have primarily fallen into three categories: 1) improving the performance of the building envelope; 2) promoting the electrical energy efficiency; and 3) strengthening the detection and management of energy consumption during the building operation phase (Rabani et al., 2017). Previous analyses have paid extensive attention to mitigation of the energy consumption from the aspect of the existing building itself and the electrical appliances inside the existing building. However, these studies have ignored the additional energy consumption caused by the aging power grid in these old communities. Accordingly, some scholars have attempted to solve this problem by transforming the power grid (Fadlullah et al., 2011; Komninos et al.,

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2014) and installing fuel cell systems (Dorer et al., 2005). But with large base and stock and the deterioration of building performance, obvious obstacles have been observed in the implementation of the two measures, including high financial cost, security problems, technical requirements and policy risks (Sun et al., 2012; Zhao et al., 2020). Therefore, it is very important to explore an effective large-scale energy saving reconstruction plan for the old residential communities (Zhu et al., 2020). Aiming at this issue, a majority of researchers have confirmed that rooftop PVs can play an important role in saving building energy on a large scale (Gagnon et al., 2018; Huang et al., 2019; Ordóñez et al., 2010; Sun et al., 2013), and studies have also attempted to assess the economic and environmental potential of rooftop PV in China (Chen et al., 2021; Qiu et al., 2021; Rodrigues et al., 2017; Sun et al., 2021). In recent years, the Chinese government has issued a series of policies to promote the development of distributed PVs (China's 12th five-year plan for renewable energy development, 2012; China's 12th five-year plan (FYP) for solar energy development, 2012; NDRC; Notice on the new-added construction plan of PV Projects in 2014, 2014). However, rooftop PV systems in the residential buildings have encountered many difficulties in practice, which is due to the lack of theoretical research on the feasibility of the installation of photovoltaic modules in residential areas. Moreover, with the rapid development and wide use of rooftop PV system energies in urban areas, the basic assessments of the actual capacity, emission reductions, and economic benefits of rooftop PVs are required. Within this context, the feasibility framework of rooftop PV system in the old community of Nanjing was established to analyze the energy saving and emission reduction potential, and to predict the feasibility of rooftop PV development in Nanjing (Fig. 1). Particularly, the solar radiation and the suitable rooftop area are calculated using BIGEMAP data and the GIS method, then the energy potential of the rooftop PV is evaluated. Furthermore, in order to evaluate the feasibility of installing rooftop PVs in the old communities of Nanjing City, the environmental and economic benefits are also quantified.

2. Literature review

2.1. Research on building energy conservation

A variety of methods can be used for energy-saving retrofits of existing buildings. From the perspective of the demand side, some studies have reduced the demand for cooling and heating energy by transforming the performance of the building envelopes (Blanco et al., 2021; Dalla Mora et al., 2015; Huang et al., 2021; Madessa, 2014) and improving the energy efficiency of household appliance (Kolokotsa et al., 2009) to reduce building energy consumption. Another set of studies investigated the impact of thermal comfort needs and living behaviors of the occupants on building energy conservation from the perspective of the residents themselves. Alev et al. (2014) selected three different types of old houses for energy-saving renovation, and they measured their thermal comfort to find energy-saving methods with the most potential. Şahin et al. (2015) designed energy-saving schemes by modeling historical buildings and examined the indoor temperature of buildings under different schemes to find the best way to meet the thermal comfort requirements. In addition, some existing study results have shown that changing the behavior of residents was also an effective method to save energy in buildings (Du and Pan, 2021; Gram-Hanssen, 2011; Şahin et al., 2015; Yue et al., 2020). Although much of this work has evaluated the energy-saving effects of building walls, windows, the electrical energy efficiency, thermal comfort, and occupant behavioral habits (Guerra-Santin et al., 2009; Ma et al., 2012), only a few studies have taken the aging power grid into consideration and tried to energize this problem by installing smart grid (Huang et al., 2012; Komninos et al., 2014; Fang et al., 2012; Franke et al., 2012). Fadlullah et al. (2011) proposed an autonomous distributed demand-side energy management system based on game theory. They developed a user-oriented energy consumption scheduling game using smart meters in the smart grid architecture to achieve the goal of reducing building energy consumption and energy costs. Park et al. (2011) used a Smart Grid Building Energy Management System (SG-BEMS) to minimize the building energy, costs, and CO_2 emissions. Others have typically applied small-scale fuel cell systems, such as polymer electrolyte fuel cell (PEFC) systems (Wallmark and Alvfors, 2003), solid oxide fuel cell (SOFC) systems (Dorer et al., 2005), and micro-cogeneration fuel cell systems (Atănăsoae, 2020) to avoid replacing aging wires and decrease building energy consumption. However, these methods either relied too much on information technology, resulting in the security and privacy of users not being effectively guaranteed or only meeting the demand for building power within a small range. Hence, they cannot be promoted at a large scale in the old residential buildings. In recent years, rooftop PV have proven to provide a great potential for building energy conservation on a large scale in the built environment (Gómez-Navarro et al., 2021; Phap and Nga, 2020; Phap et al., 2020), and provided an effective way to supply clean energy to the old residential buildings, greatly reduced the additional energy consumption from the aging power grid. Suszanowicz et al. (2019) used the GIS method to analyze the rooftop PV energy-saving potential of buildings in the old town. Hong et al. (2016) applied Hillshade analysis method to estimate the roof available area in the Gangnam District in Seoul, South Korea and assessed the physical, geographic and technical potential of rooftop PV in the area on an hourly, monthly and yearly basis. Mainzer et al. (2017) employed open earth data and image recognition techniques to obtain the roof useable area at the city level of Freiburg and identified the rooftop PV potential of 524 GWh/a. As described above, previous research has shown that the use of rooftop PVs is a trend to realize building energy conservation. Within this context, this study attempted to evaluate the energy saving potential of rooftop PV, providing some basic information for large-scale building energy conservation of the old residential buildings in urban zones.

2.2. Research on rooftop photovoltaics

Many different studies and technologies related to rooftop PVs have been developed to deal with the estimation of the rooftop PV potential. The studies were focused on the geographic potential (i.e., the useful area of the rooftop), the physical potential (i.e., the solar radiation potential of the rooftop PV), the technical potential (i.e., the electricity generation potential of the rooftop PV), the economic potential and the environmental potential of the rooftop PV in the urban zones. For instance, Izquierdo et al. (2008) predicted the suitable for rooftop PV laying based on the data of land use, population and building density, combined with urban building vector data and GIS method. Bergamasco and Asinari (2011) estimated the useful area of the rooftop PV by using the GIS (Geographic Information System) method in Piedmont region, Italy. Şenkal (2010) combined ANN and satellite data to predict solar radiation of Turkey, and the results showed a high agreement between measured and predicted values for all months. Ko et al. (2015) assessed the electricity generation potential of the rooftop PV in Taiwan based on the available rooftop area from Hillshade analysis. Gómez-Navarro et al. (2021) evaluated the technical, economic, and environmental potential of installing rooftop PV panels in the city of Valencia and found that the estimated generation capacity of rooftop PV in the study was sufficient to meet the domestic electricity demand. Mangiante et al. (2020) applied the Light Detection and Ranging (LiDAR) and local information to assess the technical and economic potential of rooftop PV development for residential buildings in Brownsville. Most of these assessment studies were based on large amounts of data or LiDAR, which have limited applicability, high cost and time consuming. It is urgent to establish a basic and efficient evaluation framework to provide baseline potential analysis maps and development suggestions for the large-scale development and utilization of rooftop PVs.

Furthermore, according to the data of Ministry of Housing and Urban-Rural Development of the People's Republic of China, By the end of 2019, China has an estimated 160000 old community, building an area of 800 million square meters (MOHURD). And Nanjing is one of the ancient capitals of China, with a huge stock of old communities too. Moreover, the residential buildings in Nanjing City before 2000 did not use thermal insulation measures (Gu et al., 2013), and these buildings would consume more energy than new energy-saving buildings. Besides, as a typical representative of hot summer and cold winter areas, Nanjing city has witnessed significantly rising average temperature, which could further drive old residential buildings consuming more energy (Li et al., 2018). Therefore, this paper studies the energy-saving potential of rooftop PV in the old residential buildings in Nanjing City and predicts the feasibility of developing rooftop PV in Nanjing. Due to the complex urban environment of Nanjing City and the limited available data, we used the roof vector images and GIS method to assess the available area of the rooftop PV in Nanjing. Based on this, a comprehensive analysis framework was established to evaluate the technical, economic, and environmental potential of rooftop PVs of the old residential buildings in Nanjing City. The following section describes the rooftop PV capacity potential, economic potential, and pollutant emission reduction potential of the old residential buildings in Nanjing City.

3. Data and methods

3.1. Study area

This study selects Nanjing City, the capital city of Jiangsu Province, as the study area (Fig. S1). It is located between 31°14″–32°37″N and 118°22″–119°14″E, with a total built-up area of 817.39 km^2 and a permanent population of 6,969,405 (2018). Nanjing has four distinct seasons and belongs to hot summer and cold winter climate zones (GB50178-93, 1993), and the annual precipitation is 1200 mm (Li et al., 2016). According to the China Standard Weather Data (CSWD, 2005), the annual average temperature is 15.4 °C; the average temperature of the coldest month (January) is 1.9 °C, and the average temperature in the hottest month (July) is 28.2 °C, the highest temperature over the years is 43.0°C (1934), the daily average temperature ≥25 °C are about 40–110 days, and the high temperature days >35 °C are about 20 days. Besides, the incidence solar radiation in Nanjing is usually high from March to October, with the annual total solar radiation of about 91.1 KWh/m^2 and the annual total sunshine of about 1982.8 h. The monthly average wind speed is 2.45–3.08 m/s, and the annual average wind speed is 2.69 m/s in Nanjing (Peng et al., n.d.). This leads to the huge demand for air conditioning in heating winter and cooling in summer. Moreover, the number of old residential buildings in Nanjing is enormous, accounting for about 46.4% of the total number of residential buildings (Li, 2017). And the old residential structure due to aging, poor energy saving effect and other problems, reduce the comfort of residents, aggravate the problem of energy consumption in Nanjing. Therefore, these old residential buildings in Nanjing City have a great potential for energy saving and emission reduction. The oldest area in Nanjing are the five central districts, namely Gulou District, Jianye District, Qinhuai District, Xuanwu District, and Yuhuatai District. Therefore, these five areas are selected as the study area.

3.2. Data

The total solar radiation data from 2017 of Nanjing City were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). The rooftop boundary data of these old residential buildings were obtained from the BIGEMAP software (BIGEMAP). And the old residential buildings basically point to 2000 or before the residential community that was built (Gu et al., 2013). The electricity consumption data for the five districts of Nanjing City in 2018 were calculated from the total number of permanent residents in each study district of Nanjing City and the electricity consumption data from the Nanjing City Statistical Yearbook (see Fig. 1).

3.3. Methods

The feasibility calculation for rooftop PV installation in Nanjing City consisted of five steps (Fig. 2). First, based on the existing studies, the solar radiation received by a rooftop PV at the optimal inclination angle was calculated. Then the suitable rooftop area was estimated using BIGEMAP data and the GIS method. The third step was to calculate the total electricity generation of rooftop PVs. The next two steps calculated the pollutant emission reduction and the economic benefits of rooftop PVs.

3.3.1. Calculation of the solar radiation

This article refers to the methods proposed by (Martín-Chivelet, 2016; Jing and Meng, 2011; Dandan and Da, 2012; Wang et al., 2021) to calculate the solar radiation under the optimal tilt angle of a PV panel (Fig. S3). The equations for performing each step are the following (Fig. S2):

First, the optimal tilt angle, β_{opt}, and spacing of the rooftop PV panels, d_s, can be calculated using the following equation:

$$\beta_{opt} = -0.0049\varphi^2 + 1.088\varphi, \tag{1}$$

$$d_s = L_{pv}\cos\beta_{opt} + \left(L_{pv}\sin\beta_{opt}\right) / \tan(66.55^\circ - \varphi), \tag{2}$$

where φ is the local latitude; and L_{pv} is the length of the photovoltaic panel (m).

The elevation angle of the sun, e, was calculated using Equations (3) ~ (5).

$$\delta = 23.45\sin[(360^\circ * (284 + n)) / 365], \tag{3}$$

$$\omega = 15(t - 12), \tag{4}$$

$$\sin e = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega, \tag{5}$$

where n is the serial number of the date. For example, the serial number of the date of January 1st is $n = 0$. In order to calculate the maximum amount of solar radiation, the summer solstice was used in this study, so $n = 173$. ω is the hour angle; t is the time, which can be any time from 0 to 24, and in this study $t = 12$; φ is the local latitude; and δ is the declination angle.

Then the atmospheric mass, m, and the atmospheric transparency coefficient P, were calculated using Equations (6) ~ (9).

$$m = \frac{1}{\sin e}, \tag{6}$$

$$\frac{P_z}{P_0} = [(288 - 0.0065L)/288]^{5.256,} \tag{7}$$

$$m(z, e) = m^*\left(\frac{P_Z}{P_0}\right), \tag{8}$$

$$P = 0.56\left[exp^{-0.56m(z,e)} + exp^{-0.096m(z,e)}\right], \tag{9}$$

where L is the local altitude, m. $m(z,e)$ is the revised atmospheric quality.

Finally, the amount of direct radiation, H_b, the amount of scattered radiation, H_d, and the amount of solar radiation, $H_{T,}$ at the optimal tilt angle were obtained as follows:

$$\frac{H_d}{H_b} = (1 - P^m) \Big/ [2P^m(1 - 1.4InP)], \tag{10}$$

$$H_d + H_b = H, \tag{11}$$

$$R_b = \frac{\left[\cos\left(\varphi - \beta_{opt}\right)\cos\delta\cos\omega + \sin\left(\varphi - \beta_{opt}\right)\sin\delta\right]}{(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta)}, \tag{12}$$

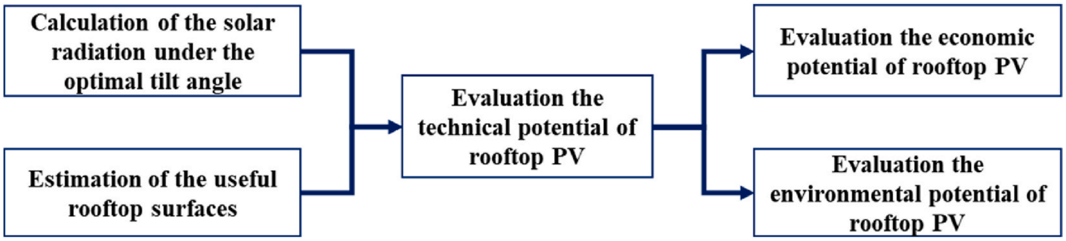

Fig. 1. Research framework chart.

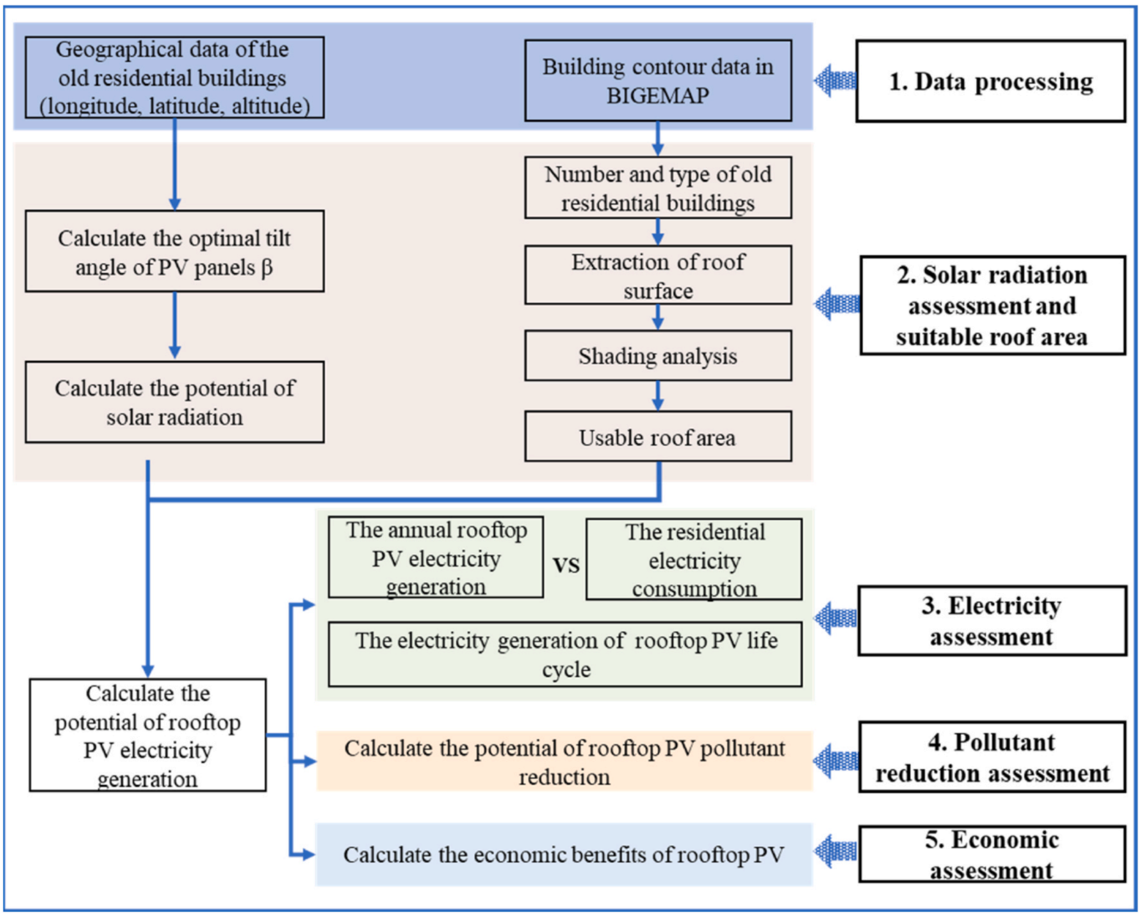

Fig. 2. Flowchart of the proposed method.

$$H_T = H_b R_b + \left[H_d\left(1 + \cos\beta_{opt}\right)\right] / 2 + \left[\varphi H\left(1 - \cos\beta_{opt}\right)\right] / 2, \tag{13}$$

where H is the global solar radiation on a horizontal surface (MJ/m^2); φ is the ground reflectivity, which is typically 0.2; and R_b is the ratio of the direct radiation amount between the inclined surface of the PV panel and the horizontal plane.

3.3.2. Identification of the useful rooftop surfaces

The research object of this paper is the old residential community in Nanjing, whose main rooftop forms are flat rooftop and sloping rooftop, and the main obstructing elements of the rooftop are the elevator shaft and the parapet.

In this study, the vector data of the building rooftop boundaries in BIGEMAP and the GIS extraction tools were applied to identify the useful rooftop areas. This allowed for the calculation of some surface areas that could affect the PV system, such as the parapets and the elevator shafts. The calculation process of the available area in the old residential area is shown in Fig. S4.

The criteria for identifying available rooftop were as follows. First, this study did not consider the area of the back sun surface of a sloped rooftop. Therefore, the area affected by the elevator, A_1, and the shadow of the elevator shaft was subtracted. Finally, the area affected by the shadow of the parapet of the flat rooftop was subtracted too. Among them, the maximum shadowed area, S_1, affected by the elevator and, S_2, affected by the parapet were as in the following equations.

$$S_1 = h_1 * \sin 29^\circ * w_1 / \tan 10^\circ, \tag{14}$$

$$S_2 = h_2 * \sin 29^\circ * w_2 / \tan 10^\circ, \tag{15}$$

where h_1 is the height of the elevator shaft; h_2 is the height of the parapet; w_1 is the width of the elevator shaft; and w_2 is the width of the parapet. In this paper, the height and width of elevator shaft and parapet refer to the main parameters of elevator, the type and size of car, shaft and machine room in the code and the standard for seismic appraisal of buildings. Therefore, the $h_1 = 3.7\ m$ and $w_1 = 2.2$ m; the $h_2 = 0.5\ m$ and $w_2 = 0.06$ m.

Therefore, the equation for calculating the available area of PV rooftop with flat rooftop was calculated as follows:

$$A_{a1} = A_T - A_1 - S_1 - S_2. \tag{16}$$

where A_T is the total rooftop areas, m^2.

For the sloping rooftop, we referred to the existing studies and assumed that the photovoltaic panels were only installed on the sunny side that received the largest amount of solar radiation (Ordóñez et al., 2010), that was, the solar photovoltaic panel array would be installed on one side of the rooftop. The calculation equation for the rooftop PV useable area of a sloping rooftop was as follows:

$$A_{a2} = A_T/2 - A_1. \tag{17}$$

3.3.3. Calculation of the rooftop PV energy generation

The energy generation of rooftop PV, E_{pv} (KWh), was calculated using the following equation:

$$A = 1 * d_{s,} \tag{18}$$

$$A_{pv} = A_a * 1/A * 1 * 1, \tag{19}$$

$$E_{pv} = \eta * A_{pv} * H_T * PR * (1 - F_s), \tag{20}$$

where A is the floor space of a solar panel (m^2), and in this study, the size of a solar panel was $1 \times 1m^2$; d_s is optimal spacing for the rooftop PV, which was obtained using Equation (2); A_a is the total useable area of the rooftop (m^2); $1/A$ is the number of solar PV panels per unit area; η is the efficiency of the PV modules; and F_s is the shading coefficient; PR is the performance ratio, According to the European PV guidelines, a typical range of PR value between 0.8 and 0.85 and less than 0.75 indicates problems with PV panels (PMGPS). Therefore, three scenarios used in energy generation assessment for rooftop PV. In this study, we assumed PR equal to 0.75, 0.8 and 0.85 respectively. This study assumed that all rooftop PV modules had the same performance and the same size for the electricity generation process. In this case, $\eta = 15\%$, *and* $F_s = 0.05$ (Martín-Chivelet, 2016).

3.3.4. Calculation of the rooftop PV emission reduction

The CO_2 and air pollutants emission reduction potential of the rooftop PV were calculated according to (China Electricity Council, 2019).

$$1 \text{ MWh of thermal power} = 841 \text{ kg of } CO_2 \text{ reduction.} \tag{21}$$

$$1 \text{ MWh of thermal power} = 0.20 \text{ kg of } SO_2 \text{ reduction.} \tag{22}$$

$$1 \text{ MWh of thermal power} = 0.19 \text{ kg of } NO_X \text{ reduction.} \tag{23}$$

The CO_2 emission potential of the residential electricity consumption were calculated by equation (24):

$$C_{re} = E_{re} \times E_C \times R \tag{24}$$

where C_{re} is the CO_2 emissions generated from the residential electricity; E_{re} is the residential electricity consumption; E_C is carbon dioxide emissions per unit of thermal power generation, which is 841 kg/MWh (China Electricity Council, 2019); R is the ratio of thermal power generation of total electricity, in this paper, the R is 73.32% of China's thermal power generation in 2018 (huaon.com.).

3.3.5. Calculation of the economic benefits of rooftop PV

The use economic benefits of rooftop PV can be divided into two situations. One is the profit obtained by a user from selling all the energy generated by the PV panel, and the other is the profit obtained by the user using part of the energy for daily household use, then selling the remaining part to the national grid. In this study, we calculated two kinds of economic benefits. First, we calculated the economic benefits generated by the annual electricity generation of rooftop PV. Since the annual electricity generation of rooftop PV was lower than the resident's electricity consumption, we assumed the second situation. Therefore, the economic benefits in this case are shown in equation (25).

$$E_{co} = \textit{the electricity price} * E_{pv} \tag{25}$$

where, the electricity price of Nanjing City in 2018 is set according to the first-range of the unified electricity price in Jiangsu Province, which is 0.5283 CNY/KWh.

Second, we use a net present value approach to assess the economic viability of rooftop PV over the life cycle. In this paper, the economic benefits of life cycle power generation were divided into two types. One was to sell all the power generation in the life cycle to the power grid, we defined that as Scenario 1; the other was to use all the power generation in the life cycle for self-use, we defined that as Scenario 2. Since the total annual electricity generated by rooftop PV was only 17.1%–20% of the residential electricity, this study did not consider the third case of self-use and surplus electricity sold to the power grid. Net present value (NPV) is usually used to represent the annual benefit of the project, and it is one of the commonly used indicators to assess the economic benefits of the project (Lee, 2016; Ren et al., 2018). The calculation equation for NPV is shown in equation (26-29). We assume a service life of 25 years for the PV panels. The standard battery pack size is $1650 \times 990\ mm^2$, the component power is 260wp, then the installed power per square meter is $159.17 wp/m^2$ (Liu et al., 2016). The initial cost of rooftop PV is about 4.19 CNY/W (Zhao and Xie, 2019), the decay rate of rooftop PV panels is 3% in the first year, 0.7% per year thereafter, the annual maintenance cost of rooftop PV in residential buildings is 0.07 CNY/W (Zhao and Xie, 2019), and the cost of other rooftop PV system components are listed in Table S1.

$$NPV(i) = \sum_{i=0}^{T} F_t (1+i)^{-t} \tag{26}$$

$$F_t = CI - CO \tag{27}$$

$$CI = \sum_{i=0}^{T} \left(E_{om,\,i} - E_{o,\,i}\right) \times v_1 + \sum_{i=0}^{T} E_{o,\,i} \times v_2 + v_3 \tag{28}$$

$$CO = C_{ivs} + C_M + C_B + C_I \tag{29}$$

where, $NPV(i)$ is the net present value; i stands for the financial discount rate, which is assumed 10% (Yuan et al., 2014); t represents the service time of PV panels, which is assumed 25; F_t is the Net cash flow, which is the difference between CI and CO; CI is the annual cash inflow; CO is the annual cash outflow; $E_{om,\,i}$ is the power generation in year i; v_1 is the benchmark price of desulfurization, and the v_1 in Jiangsu Province in 2018 is 0.391 CNY/KWh; $E_{o,\,i}$ is the user's self-used electricity generation in year i; v_2 is the local power grid electricity price, and the v_2 in Jiangsu Province in 2018 is 0.5283 CNY/KWh; v_3 is other revenue of the system, such as other subsidies from the government, the v_3 for self-use of the distributed PV in Jiangsu Province, China in 2018, is 0.37 CNY/KWh, and the subsidy period is 20 years; the v_3 for all feed-in tariff of the distributed PV in Jiangsu Province, China in 2018, is 0.7 CNY/KWh, and the subsidy period is also 20 years. C_{ivs} is the initial cost rooftop PV; C_M is the maintenance cost of rooftop PV in residential buildings; C_B is the replacement cost of battery of rooftop PV, the two scenarios of this study do not need to consider for cell storage, and therefore the replacement cost of battery of rooftop PV is 0; C_I is the replacement cost of inverter of rooftop PV, which is 600 CNY/KW (Zhang et al., 2021). The middle exchange rate in the results was 6.5263CNY/US$(Ji et al., 2019).

4. Results

4.1. Useful area of the rooftop PV system

Fig. S5 shows the geographical distribution of all the old residential buildings in the five central districts of Nanjing City. Among the five districts covered by the data we collected, the number of old communities accounted for 40.36% of the total number of communities, and the suitable area for rooftop PV installation only accounted for 61% of the total rooftop area of the old communities. As shown in Fig. 3, Qinhuai and Gulou had the largest number of old residential buildings, while Jianye and Yuhuatai had the least number, especially the Yuhuatai District. Then the total useable areas of the rooftop in the five districts were 2.22 km^2 in Gulou, 0.95 km^2 in Jianye, 1.93 km^2 in Qinhuai, 1.19 km^2 in Xuanwu, and 0.46 km^2 in Yuhuatai.

4.2. Estimation of the rooftop PV electricity generation

As shown in Fig. 3, the solar radiation value in the five districts of Nanjing was relatively stable, with an average annual solar radiation of 5219.04 MJ/m2. In absolute numbers, the higher annual total solar radiation was found in Yuhuatai, which was 5230.80 MJ/m2, and the minimum was in Gulou, which was 5210.41MJ/m2. Besides, the total annual electricity generation of rooftop PV in these five districts of Nanjing was approximately 741.25 GWh (PR = 0.85), 697.65 GWh (PR = 0.8), 654.04 GWh (PR = 0.75), respectively. In terms of the total annual rooftop PV electricity generation of the five districts of Nanjing, Gulou District and Qinhuai District had the largest electricity generation, followed by Xuanwu District and Jianye District, and Yuhuatai District had the smallest electricity generation (Fig. 3). The electricity consumption of the urban and rural residents was 3986.98 GWh (Statistical Yearbook of Nanjing, 2019) in the year of 2018 in these five districts (Fig. S6). And the total annual electricity generation of rooftop PV accounts for about 20% (PR = 0.85), 19% (PR = 0.8) and 17.7% (PR = 0.75) of the resident's electricity consumption. From the calculation results of the life cycle electricity generation of rooftop PV, when the performance of photovoltaic panels (PR) was 0.85, 0.8, and 0.75, the life cycle electricity generation of rooftop PV in the five districts of Nanjing was 16543.35 GWh, 15570.22 GWh, and 14597.08 GWh, respectively (Table S2).

4.3. Environmental assessment

Fig. S7 details the pollutant reduction potential for rooftop PVs in the five districts. Under the three electricity generation scenarios of rooftop PV, the two areas with the largest pollutant emission reductions were Gulou and Qinhuai. However, the Xuanwu, Jianye, and Yuhuatai Districts had a lower pollutant reduction potential. In terms of pollutant types, CO_2 has the largest emission reduction, followed by SO_2 and NO_X. Besides, similar to Table S3, when the performance of photovoltaic panels (PR) was 0.85, 0.8, and 0.75, the life cycle CO_2 emission reductions of rooftop PV in the five districts of Nanjing was 13912874.12t, 13094469.76t, and 12276065.4t, respectively; the life cycle SO_2 emission reductions of rooftop PV in the five districts of Nanjing was 3308.65t, 3114.02t, and 2919.40t, respectively; and the life cycle NO_X emission reductions of rooftop PV in the five districts of Nanjing was 3143.22t, 2958.32t, and 2773.43t, respectively. In comparison, as shown in Fig. S8, the CO_2 emission reductions of residential electricity

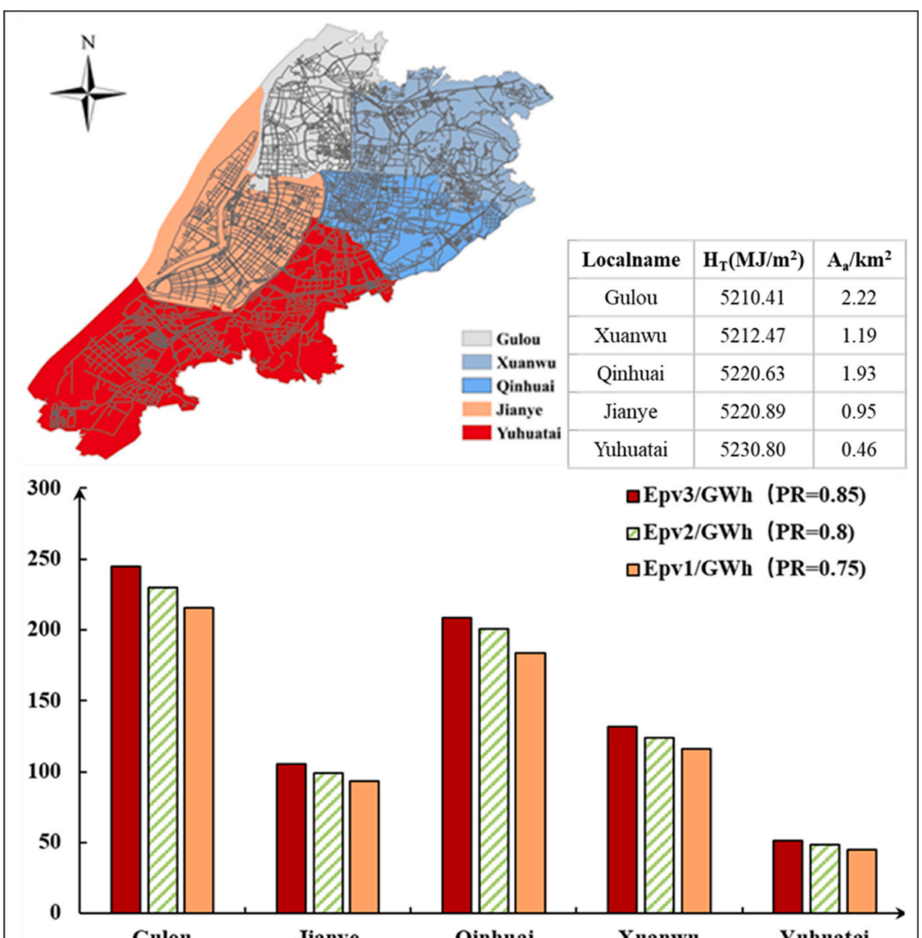

Fig. 3. Solar radiation potential, useable rooftop area and the rooftop PV electricity generation potential.

consumption in the five districts of Nanjing was 22734731.04 t.

4.4. Economic benefits

Fig. S9 showed the results of the income generated by residents' self-use based on the total annual electricity generation of rooftop PV. The results showed that the total annual income of rooftop PV in the five districts of Nanjing was 102 Million US$ (PR = 0.85); 96.03 Million US$ (PR = 0.8); 90.02 Million US$ (PR = 0.75). Similarly, Gulou and Qinhuai Districts showed the greatest economic gains. Table S4-S6 showed the economic benefits of rooftop PV life cycle power generation. The total life cycle investment of the rooftop PV was 7676444676 US$. In scenario 1 (the life cycle generation of rooftop PV was sold to the grid), the total income was 2148659577 US$ (PR = 0.75), 2291903549 US$ (PR = 0.8), 2435147521 US$ (PR = 0.85); The NPV of the life cycle was −2323244831 US$ (PR = 0.75), −2258599102 US$ (PR = 0.8), and −2193953374 US$ (PR = 0.85). In scenario 2 (the life-cycle power generation of rooftop PV was for self-use), the life cycle revenue of rooftop PV was 1855092017 US$ (PR = 0.75), 1978764818 US$ (PR = 0.8), 2102437619 US$ (PR = 0.85); The NPV of the life cycle was −2483849300 US$ (PR = 0.75), −2429910536 US$ (PR = 0.8), and −2375971772 US$ (PR = 0.85).

5. Discussion

This study established an analytical framework to evaluate the technical, economic and environmental potential of rooftop PVs for energy-saving and abatement feasibility of rooftop PVs in the five districts of Nanjing City, which is universal and can be extrapolated to other cities in China to overcome the limitations of the lack of high-resolution urban building images and the high cost of estimating the potential of rooftop PVs.

From the results of the research on the electricity generation of the rooftop PV, the annual power generation of rooftop PV in old residential buildings in Nanjing is far less than the electricity demand of residents, and the power generation of rooftop PV of the old residential buildings in the five districts can only meet the electricity demand of 17.7%–20% of the residents. If these old residential buildings are completely mounted with the rooftop PV, the production of rooftop PV from each old residential cell is expected to be consumed by the residents themselves. Therefore, we speculate that the development of rooftop PV in the old residential buildings in the five districts of Nanjing City will have no or only a small fraction of the electrical capacity to flow into the grid for other households, and therefore, the PV system may not need to install storage cells. From the results of the emission reduction potential of rooftop PV, the largest value was found when PR = 0.85, but the total emission reduction potential of rooftop PV in the old residential buildings in the five districts of Nanjing is still low compared with the CO_2 emission generated by electricity consumption of the residents, which is 13912874.12t (Fig. S7 and Fig. S8). In terms of economic benefits, no matter what scenario, rooftop PV life cycle power generation on the old residential buildings in the five districts of Nanjing City cannot generate economic benefits, with NPV value less than 0. This is mainly due to the still high cost of rooftop PV systems and maintenance (Fig. S10). From this perspective, the distributed PV subsidy policy developed in Jiangsu Province in 2018 may not be attractive to residents, and the effectiveness of installing rooftop PV is questionable. Therefore, it is doubtful that it is feasible to develop rooftop PV in old residential buildings of Nanjing City to meet the target of energy saving and emission reduction.

Consequently, these serious problems must be considered when developing rooftop PV in Nanjing, and other research results can be referred to alleviate this problem, such as the introduction of centralized photovoltaic (Y. Sun et al., 2013) or other clean energy (MAO et al., 2021). Moreover, according to the results of the economic benefits assessment of rooftop PV, the installation of rooftop PV in old communities in Nanjing cannot generate high returns, especially when the cost of distributed PV systems is high (Martinopoulos, 2020). Based on the above analysis results, we suggest that the government of Nanjing City should seriously consider promoting rooftop PV to achieve the goal of energy conservation and emission reduction, and appropriately increase the subsidy of kilowatt-hours rooftop PV or have the government subsidize users to purchase solar PV panels in the process of developing rooftop PV, so that the roof PV has more potential for development. In addition, the government should emphasize the use of rooftop PV in infrastructure buildings such as schools and hospitals, as well as buildings in rural areas, to help achieve the goal of "carbon neutrality" by 2060.

6. Conclusions

This study established a framework and technical method for evaluating the rooftop PV potential of the residential communities in China. This paper selected five old districts of Nanjing City as the research object to analyze the potential and feasibility of energy-saving and emission reduction of rooftop PV in the residential communities in Nanjing. The following conclusions can be drawn from the above analysis:

(1) In the five districts of Nanjing City, the highest useful rooftop areas and electricity generation of rooftop PV were Gulou district and Qinhuai district. Therefore, these two districts should be given priority when promoting rooftop PV in Nanjing old residential communities.
(2) The old residential communities in Nanjing City have low environmental and economic potential of rooftop PV. From the perspective of economic benefits, Nanjing City may not suitable for large-scale promotion of rooftop PV to achieve building energy saving.
(3) The economic benefits of rooftop PV are affected by government subsidies, PV panel costs, PV battery costs, operation and maintenance costs, and PV panel performance. The high cost of PV components and the continued reduction of government subsidies would lead to the rooftop PV being an unattractive investment. Therefore, these factors need to be considered when developing rooftop PV.

These conclusions provide evaluation method references for the application of rooftop PV in large-scale energy-saving renovation in cities, and also provide theoretical guidance for the development of rooftop PV plans by energy sectors in China.

CRediT authorship contribution statement

Peng Wang: Conceptualization, Methodology, Formal analysis. **Ping Yu:** Writing – original draft, Data curation, Software. **Lei Huang:** Validation, Writing – review & editing. **Yuhu Zhang:** Visualization, Investigation.

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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Appendix A. Supplementary data

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