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GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province

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HIGHLIGHTS

- We developed a grid-based comprehensive potential analysis framework of solar energy at the regional scale.
- We evaluated the technical potential of solar PV generation.
- We calculated the cost of PV generation and got the geospatial supply curve (GSC) of Fujian Province.
- PV technology provides high potential for roof-top application and large-scale PV stations.
- Determining a reasonable feed-in tariff is essential for expanding the application of solar PV energy.

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ABSTRACT

Spatial variation of solar energy is crucial for the estimation of the regional potential and selection of construction location. This paper presents a case study of using high resolution grid map of solar radiation combined with the other restriction factors to evaluate the comprehensive potential analysis of solar PV generation at the regional scale, in order to present a framework of decision support tool for solar energy management in a regional area. The cost of PV generation is calculated based on the geographical distribution of technical potential. Moreover, geospatial supply curve (GSC) is employed to portray the evolution of available potential of photovoltaics (PV) generation with the increase of the generation cost. By integrating the economic evaluation variables of net present value and simple payback period, grid-based economic feasibility of PV generation project is then carried out under two feed-in-tariff scenarios. Finally, total CO_2 reduction potential and its spatial distribution in the study area are calculated. The results confirm that PV technology provides high potential for roof-top application and large-scale PV stations. Additionally, determining a reasonable feed-in tariff is essential for expanding the application of solar PV energy. The findings improve understanding of regional renewable energy strategies and the supply/demand assessment.

1. Introduction

Most Chinese cities currently experience rapid urbanization and economic growth. Therefore, improvement in energy efficiency and promotion of clean and renewable energy development might play the most important role in energy conservation and greenhouse gas (GHG) reduction (Lin et al., 2010; Xiao et al., 2011). Solar power is the conversion of sunlight into electricity, directly using PV, or indirectly using concentrated solar power (CSP). PV electricity is one of the best options for sustainable future energy requirements of the world. At present, the PV market is growing globally at an annual rate of 35–40%, with PV production around 10.66 GW in 2009 (Razykov et al., 2011). In the same year, China has newly installed PV capacity of 160 MW, and with the total installed capacity of 300 MW. China is about to raise its 2015 goal for solar photovoltaic (PV) power to 10 GW in the newly submitted “Development Plan for Renewable Energy during the 12th Five-Year Period” (Xu, 2011). If it is realized, China′ PV market will usher in an era of speeding up development.

The market development of solar energy is strongly dependent on the policy, technology development and transfer, economics of solar energy products, and the local solar energy resource. It is necessary to integrate all these influencing factors to analyze the potential of solar energy as a source for producing electricity and plan the exploitation of solar energy in a given area. Spatial information technologies, particularly Geographical Information

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Systems (GIS), have been widely used in evaluating the feasibility of solar power stations in a given region and identifying optimizing locations. During the last decade, considerable effort has been expended to obtain Decisions Support Systems (DSS) tools in order to facilitate renewable energy at a regional scale (Domínguez and Amador, 2007). The main objectives of such studies were to evaluate the potential of renewable energy resources through integrating data of various constraints factors. For example, Hoogwijk (2004) presented a comprehensive analysis using a grid cell approach to assess the geographical, technical and economic potential of renewable energies at the regional and global scales. Clifton and Boruff (2010) integrated the local environmental variables and electricity infrastructure on a high resolution grid to identify the potential for CSP to generate electricity in a rural region of Western Australia. Charabi and Gastli (2011) assessed the land suitability for large PV farms implementation in Oman using GIS-based spatial fuzzy multi-criteria evaluation. Janke (2010) identified areas that are suitable for wind and solar farms using multi-criteria GIS modeling techniques in Colorado. Additionally, rooftop PV is a main application form of distributed solar generation in built-up area. In order to estimate the rooftop PV potential for a large-scale geographical region, various modeling technologies have been developed in recent studies. Wiginton et al. (2010) demonstrated techniques to merge the capabilities of GIS analysis and object-specific image recognition to determine the available rooftop area for PV deployment. Kabir et al. (2010) identified and calculated bright roof-tops of Dhaka Megacity from Quickbird high-resolution optical satellite imagery in order to assess power generation potential through solar photovoltaic applications. Liu et al. (2010) built a model with taking both natural and social restriction factors of solar resources into consideration to evaluate the available roof-mounted solar energy resource in Jiangsu Province.

Due to the higher development cost of solar energy, economic feasibility is very critical for implementing regional solar energy projects. Sun et al. (2011) studied the economic and environmental benefits of the grid-connected PV power generation system in China' 34 province capital cities using the net present value and the single factor sensitivity analysis tools. Ramadhan and Naseeb (2011) determined the economic feasibility and viability of implementing PV solar energy in the State of Kuwait. The cost analysis showed that when the value of saved energy resources was used in producing traditional electricity, and the cost of lowering CO_2 emissions were accounted for, the true economic cost of the levelized cost of electricity (LCOE) of a PV system would decline significantly. Poullikkas (2009) carried out a feasibility study in order to investigate whether the installation of a parabolic trough solar thermal technology for power generation in the Mediterranean region was economically feasible. His case study took into account the available solar potential for Cyprus, as well as all available data concerning current renewable energy sources policy of the Cyprus Government. However, the study did not take the spatial variability of solar radiation into account.

GIS is a power tool to perform spatial multi-criteria decision analysis integrating geographical spatial data for a comprehensive feasibility assessment of solar energy potential at the regional scale. The solar energy potential evaluation and economical feasibility analysis need to be evaluated together to identify the areas that have economically competitive renewable resources. Spatial explicit assessment of solar radiation is a key element of improved feasibility methodology framework present here. To integrate the potential evaluation and economical analysis for solar energy, this study developed a grid-based comprehensive potential analysis framework of solar energy at the regional scale for technical users and economic decision-makers. A case study of the approach is implemented for Fujian Province, China.

2. Study area

The study area of this research is Fujian Province, which lies in the southeast coast of China facing Taiwan across the Taiwan Straits, and is divided into nine prefecture-level divisions. The province covers an area of over 139,000 square kilometers and has a population of 36.89 million (2010). The province capital is Fuzhou. Fujian has a mild and humid climate and its mean temperature in the coldest month of January is 5 °C (41 °F) in the northwest and 12 °C (53.6 °F) in the southeast. In the hottest month of July, it has an average temperature of 25–30 °C (77 –86 °F). Over the past three decades of “Reform and Opening”, Fujian has experienced spectacular economic growth. Energy consumption in Fujian Province has undergone a dramatic increase in last three decades, with an annual growth rate of 8.46%. Annual energy consumption reached 82.83 million tons of coal equivalents (TCE) in 2008; most of the energy consumed comes from fossil fuels (84%) and hydroelectric power (15.8%). Wind power and other forms of renewable energy are at a very early stage of development and provided only 0.2% of the whole energy consumption (Statistics Bureau of Fujian Province, 2009). About 60% of energy consumed comes from outside Fujian. This percentage is expected to grow in the future, indicating a serious threat to Fujian's energy security and economic growth (Wang et al., 2011). In this context, the large-scale application of renewable energy is taken as main measures to address the current challenges of supply shortage of primary energy and to achieve the target of carbon emission reduction.

3. Methodology

This study presents a GIS-based approach to facilitate the feasibility analysis of investments for policymakers, investors and energy planner in a given region. The procedure is comprised of two steps: the first step is to evaluate the potential for exploiting solar energy sources, including geographical and technical potential in suitable areas with the aid of GIS spatial analysis functions. The second step is to assess economic feasibility for PV generation. Continuous cost surface for PV generation is calculated based on the technical potential in the study area. Next, a solar geospatial supply curve is developed following a GIS method of the National Renewable Energy Laboratory (NREL) (Kline et al., 2008). To analyze the returns and risks on PV investment, the financial analysis of investments is conducted in this study with a cash flow analysis based on the following economic parameters: net present value (NPV) and simple payback period (SPP), according to the expected energy outputs, and energy costs. The framework of the methodology is illustrated in Fig. 1.

3.1. Estimation of solar radiation

To exactly estimate the solar radiation for the study area, a high resolution solar radiation map for Fujian Province was calculated by using the solar radiation analyst module of ArcGIS 9.3, which has been used in published literatures (Clifton and Boruff, 2010; Gastli and Charabi, 2010). The module accounts for atmospheric effects, site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography, and it allows to modify the coefficient of the atmospheric transmissivity (Charabi and Gastli, 2011). The model estimates the total amount of radiation as the sum of direct and diffuse radiation of all sunmap and skymap sectors. The main input parameters to the model were a 90 m × 90 m digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) and coefficient of the atmospheric transmissivity. The DEM data set is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese

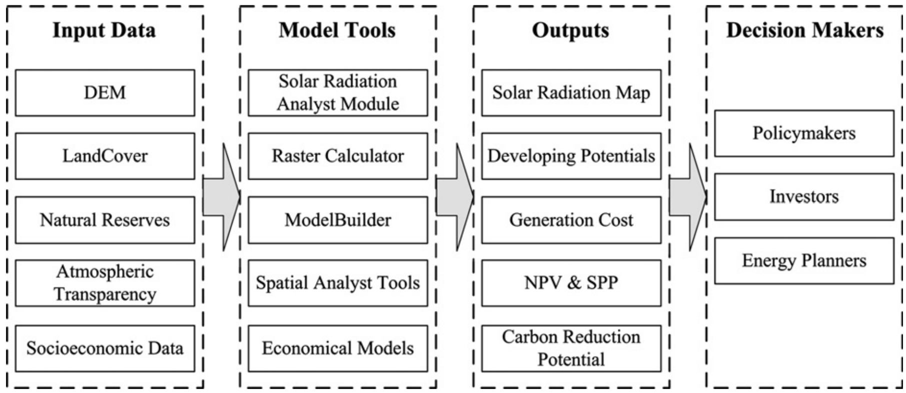

Fig. 1. Framework of the methodology for evaluating the feasibility of investments in exploiting regional solar energy sources.

Academy of Sciences (http://datamirror.csdb.cn). According to the study conducted in Fuzhou city (Collaborative Group of Solar Energy, 1980), an average annual transmissivity value of 0.63 was adopted. The resulting grid maps contain 12 monthly and the yearly sum of the global horizontal radiation in Fujian Province.

3.2. Estimation of solar PV generation potential

For assessing the amount of electricity potential from solar PV, we follow the hierarchical methodology developed by Hoogwijk (2004) and Gómez et al. (2010). The three categories of potential are defined in this study:

- Geographical potential: defined as the amount of the total yearly solar radiation over the regional suitable area, and in the process of evaluation several geographical constraint factors have been taken into consideration;
- Technical potential: defined as the amount of the total geographical potential that can be converted into electricity energy using PV systems;
- Economic potential: defined as the amount of the total technical potential that can be generated at costs that are competitive with conventional electricity sources.

3.2.1. Estimation of geographical potential

Geographical potential analysis identifies the suitable land areas for constructing the PV plants taking the geographical constraints into account. Generally, there are two kinds of application models for solar PV generation: (a) for the suitable area outside of built-up areas and it means for large-scale PV station; (b) for the built-up areas, the roof-top PV is the main system. In this study, we estimate the potential of these two deployment models in the study area, respectively. Based on the previous studies (Clifton and Boruff, 2010), geographical restriction areas for the outside of built-up area is referred to water body, natural reserve, agriculture land and land with slopes of more than 4°. The GlobCover 2009 land cover products (with a 300 m resolution) derived from ESA and UCLouvain (2010) was used to extract the built-up areas and geographical restriction areas. The overall accuracy of the Globcover classification weighted by class area is 73%, and was derived using a reference dataset of 3167 points globally distributed across both homogeneous and heterogeneous landscapes. The slope data set is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (2010) (http://datamirror.csdb.cn). The map algebra function of ArcGIS is used to merge and reclassify all the layers. The suitable areas are then determined by excluding the geographical restriction. So the solar PV potential for the suitable area outside of built-up areas area can be calculated by multiplying annual total amount of solar radiation in the grid cell i by area of unit grid cell.

To quantify the roof-top solar PV potential in the built-up area, we use the following equations:

$$W_i = B_i \delta \alpha \tag{1}$$

$$P_i^G = R_i W_i \tag{2}$$

where W_i is the available roof area in the grid cell i; B_i is the area of the built-up area in the grid cell i; δ is the ratio between the area of building roof-top and the total area of built-up, α is the popularizing ratio of roof-mounted PV system; P_i^G is geographical potential in the grid cell i in the built-up area; R_i is annual total amount of solar radiation in the grid cell i. One good way to identify the building roof areas is using the object-specific image recognition from high resolution image data set like Quickbird satellite data with a 0.6 m resolution (Kabir et al., 2010; Wiginton et al., 2010). Due to the various factors like planning function, shadow of the roof areas and so on, the possible roof-mounted areas or the popularizing ratio fluctuate very much. In this study we take δ as 0.2 (generally, the ratio ranges from 0.15 to 0.3 in most studies) and the popularizing ratio α as 0.3 just for an assessment result.

3.2.2. Estimation of technical potential

Technical potential analysis estimates the available solar energy in the geographical potential through taking the technical characteristics of PV generation system into consideration. The PV production energy is determined by three main parameters, solar radiation of local area, and size and performance ratio of PV systems. The annual total amount of PV generation electricity in the grid cell i, E_i, was calculated using the following equation:

$$E_i = \frac{P_i G_i \eta_T}{1000\ w/m^2} \tag{3}$$

where P_i is the peak power of PV system installed in grid cell i, G_i is the annual total amount of global radiation on the horizon in grid cell i, η_T is the performance ratio of PV system. A typical value for PV system with modules from mono- or polycrystalline is around 0.75 (Šúri et al., 2007).

3.2.3. Economic potential of solar energy

To show the spatial distribution of PV generation cost and construct the geospatial supply curve, the PV generation costs for all grid cells in the study area is calculated. The total production cost of solar PV energy mainly comprises initial investment, as well as operation and maintenance costs. Total initial investment cost is the sum of PV system costs and construction cost. The annual operation and maintenance costs are taken to be constant and defined as fraction of investment cost. The transmission cost is neglected. Consequently, the unit cost of the energy generation in grid cell i is calculated using the equations:

$$PC_i = \frac{L + C_{O\&M}}{E_i} \tag{4}$$

$$L = I\frac{r(1+r)^N}{(1+r)^N - 1} \tag{5}$$

where PC_i is the cost of 1 kW h of electricity generated in a grid cell i, I is the initial investment cost depending on the PV system size, E_i is the energy yield in grid cells i, r is the nominal discount rate (taken as 9%), N is the life time of the system (25 years). $C_{O\&M}$ is the operation and maintenance costs, and it was assumed to be of a constant rate (0.03 of investment) over the life time of installation. L is the annual loan payment. In order to simplify the calculation process, it is assumed that the total investment of PV plants is obtained completely from loans and the method of repayment is the matching loans repayment.

Following the methods in other studies (Kline et al., 2008; Hoogwijk, 2004), geospatial supply curves (GSC) were produced through combining the cost model with the technical potential. The GSCs can answer three key questions: (1) How much solar energy is available at or below a given price? (2) Conversely, given a desired level of installed capacity, how much will the delivered energy cost? (3) Which locations can supply energy at or below a given price? The answers to these questions provide a foundation for a more comprehensive regional planning that would address additional infrastructure, planning, and policy questions.

3.3. Economic feasibility for PV investment

The cost-benefit analysis is critical for appraising the feasibility of PV projects. In order to identify the potential regions that have economically competitive solar energy resources with acceptable levels of financial risk, the financial analysis of investments was carried out in this study by the following financial parameters: net present value (NPV) and simple payback period (SPP), according to the expected energy outputs, energy costs, and two feed-in tariff (FIT) scenarios. In finance, the NPV is defined as the sum of present values of the difference between the present value of cash inflows and the present value of cash outflows. NPV is a central tool to analyze the profitability of a long-term project. The NPV in grid cell i can be expressed as the following equation:

$$NPV_i = \sum_{n=1}^{N} \frac{B_n - (L + C_{O\&M} + C_{Tax})_n}{(1+r)^n} - I \tag{6}$$

where B_n is the annual income from PV production for the nth year; r is the discount rate, assumed to be a constant in the future ($r = 0.08$).

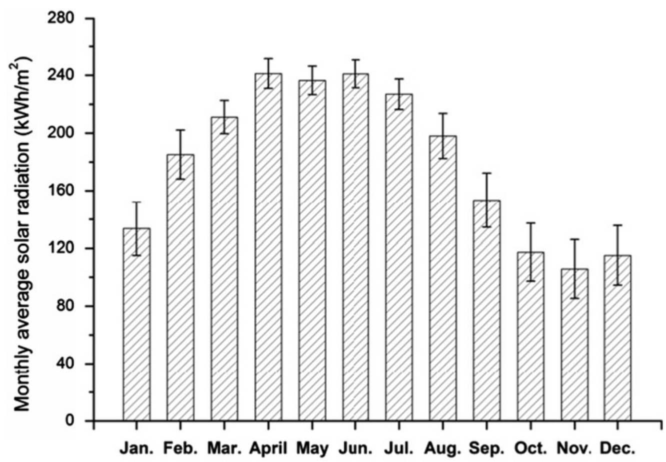

Fig. 3. Seasonal variability of solar radiation for Fujian Province.

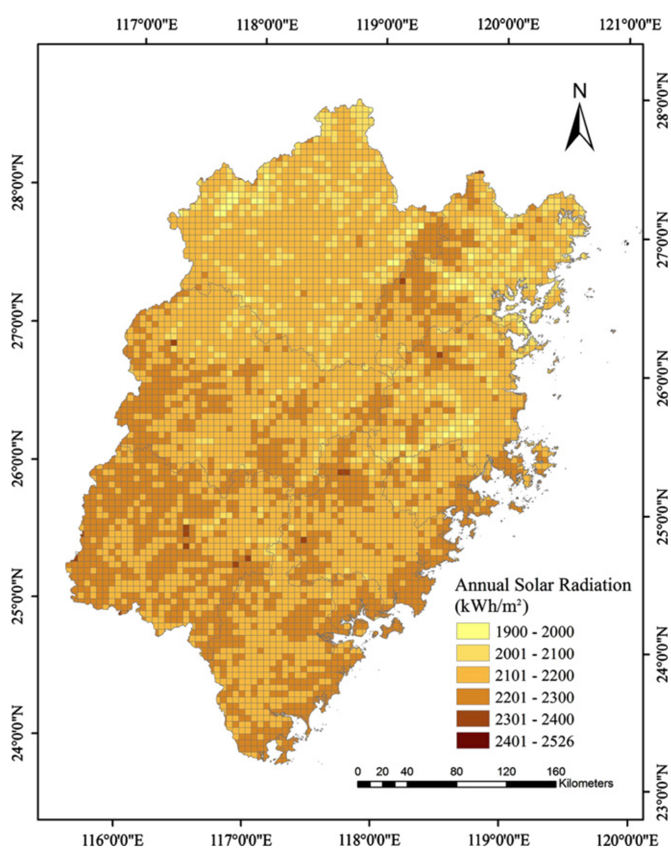

Fig. 2. Spatial distribution of annual solar radiation for Fujian Province (kW h/m²).

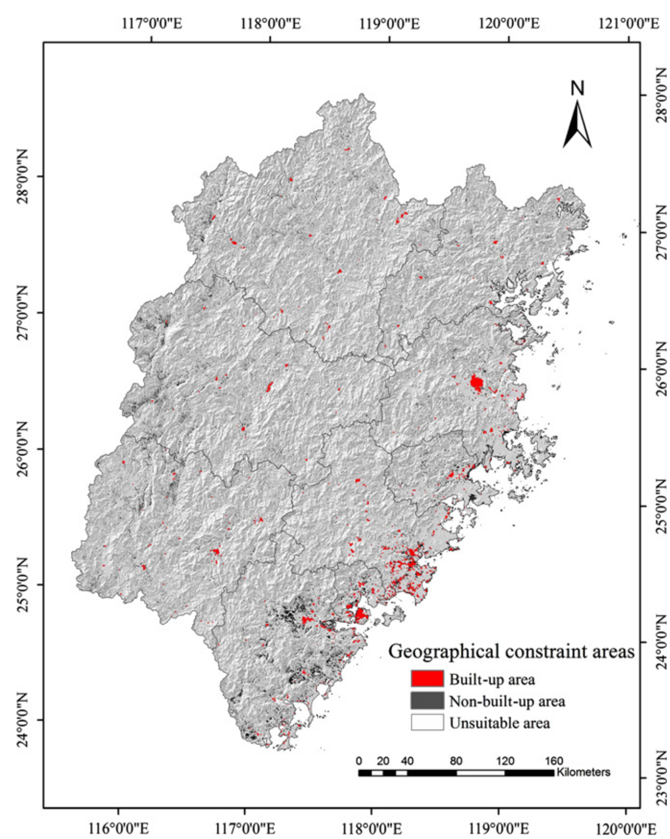

Fig. 4. Spatial distribution of the geographical constraint areas.

The SPP is the length of time required for cumulative incoming returns to equal the cumulative costs of an investment, usually measured in years. This indicator can reflect the risk and uncertainty of investment project in a certain extent. A shorter payback period is viewed as less risky. The equation for the calculation of SPP in grid cell i is as follows:

$$PY_i = \frac{I}{B_i} \tag{7}$$

The annual income from PV production in grid cell i is calculated by the annual output in grid cell i multiplied by the assumed FIT.

The above two financial indicators can help the investors and energy planner to determine the preferential exploited region.

ArcGIS modelbuilder allows for automating GIS processes by linking data input, ArcGIS tools/functions, and data output, and is an easy-to-use application for creating and running workflows containing a sequence of tools. In this study, model builder was used to create a GIS model to calculate the financial indicator of NPV in each pixel. The model required input data including annual electricity production and economical parameters like initial investment, O&M costs, annual loan payment and FITs.

In order to clearly present the spatial trends of above analysis results, the maps were gridded with 5 km × 5 km units. The whole territory of Fujian was therefore divided into 5377 square grids. The value of each grid unit was calculated based on cell values within the zones using the Zonal Statistic tools (sum or average).

4. Results and discussion

4.1. Solar energy resource in Fujian Province

The solar energy resource is determined by latitude, continentality, terrain and local climatic variations (Šŭri et al., 2007). The spatial variation of annual global solar radiation on the horizon in the study area is shown in Fig. 2. The value on each grid unit represents the sum of cell values within the zones. On the base of primary estimation results, annual solar radiation differs in value over the region from 788 to 2670 kW h/m^2. The central mountain area and southern area are endowed with excellent solar energy resource. Several cities in the southeastern coastal area are power load centers, including Zhangzhou, Xiamen, Quanzhou and Putian, which have annual solar radiation above 2200 kW h/m^2.

The seasonal variability of the solar energy in the study area is very important information for planning the power grid management. Fig. 3 shows the seasonal variability of monthly average solar radiation in the study area. Notice that the highest value is obtained during the summer month (June) and the lowest value is obtained during the winter month (November). Standard deviations of solar radiation autumn–winter are higher compared to spring–summer months.

4.2. Geographical potential

To find out the suitable location for PV plants in the study area, the land cover and DEM database were used to extract the geographical constraint factors. The suitable areas were divided into built-up area and non-built-up area. The suitable area for PV plants in the built-up area and non-built-up area is illustrated in Fig. 4. For non-built-up area, the suitable area accounts for 19% of the total area (about 6511 km^2), where 14.46 PW h/year can be obtained from the solar radiation on the horizon. For built-up area, the available building roof area is about 72 km^2, when assumed the popularizing ratio α to be 0.3. The theoretical potential is estimated to be 157 TW h/year of solar radiation that can be received on the horizontal roof-top surface. The regional geographical potential is estimated to be 14.62 PW h/year.

The geographical potential of solar energy for nine prefecture-level cities in Fujian Province is quantitatively summarized in Tables 1 and 2. As shown in Table 1, the difference of annual average solar radiation between nine prefecture-level cities is very small, and it decreases with increasing latitude. However, there are large geographical differences for geographical potential between nine prefecture-level cities

Table 1
Geographical potential of solar energy in the non-built-up area for nine prefecture-level cities in Fujian Province.

Prefecture-level cities	Total area of prefecture-level cities (km^2)	Annual average solar radiation (kW h/m^2)	Min. value of solar radiation (kW h/m^2)	Max. value of solar radiation (kW h/m^2)	St. deviation (kW h/m^2)	Suitable area (km^2)	Geographical Potential (TW h/year)
Sanming	22,929	2230	1526	2578	60	1339	2986
Nanping	2,628	2179	1628	2540	61	1194	2601
Zhangzhou	12,874	2227	1652	2538	41	1147	2555
Longyan	19,028	2246	1578	2583	71	1000	2246
Ningde	13,452	2219	1589	2524	83	567	1259
Fuzhou	12,155	2221	1692	2568	72	501	1113
Quanzhou	12,874	2233	1508	2582	72	402	898
Putian	4,119	2225	1508	2552	62	247	549
Xiamen	1,652	2223	1721	2454	41	115	255

Table 2
Geographical potential of solar energy in the built-up area for nine prefecture-level cities in Fujian Province.

Prefecture-level cities	Total area of built-up area (km^2)	Annual average solar radiation (kW h/m^2)	Min. value of solar radiation (kW h/m^2)	Max. value of solar radiation (kW h/m^2)	St. deviation (kW h/m^2)	Suitable area (km^2)	Geographical Potential (TW h/year)
Quanzhou	365	2217	1569	2432	48	22	49
Fuzhou	190	2178	1462	2350	54	11	25
Zhangzhou	174	2228	1614	2432	46	10	23
Xiamen	139	2227	1765	2384	43	8	19
Longyan	85	2224	1604	2500	75	5	11
Nanping	83	2144	1532	2442	91	5	11
Sanming	56	2173	1570	2498	89	3	7
Putian	52	2211	1783	2318	32	3	7
Ningde	42	2154	1556	2407	87	3	5

due to the differences of total suitable area. It is obviously that the highest potential of solar energy is in Sanming, and lowest potential in Xiamen. The highest proportion of suitable area is found in Zhangzhou because of its flat terrain and large total area.

Table 2 showed that the geographical potential of the coastal region, including Quanzhou, Fuzhou, Zhangzhou and Xiamen is large for roof-top PV utility, because of this region with large building roof area and relatively higher solar energy resource. Furthermore, the southeastern coastal area of Fujian concentrated around 64% of total population and 63% of GDP. Thus, residential and commercial building roof-top PV systems have better application prospect in this region.

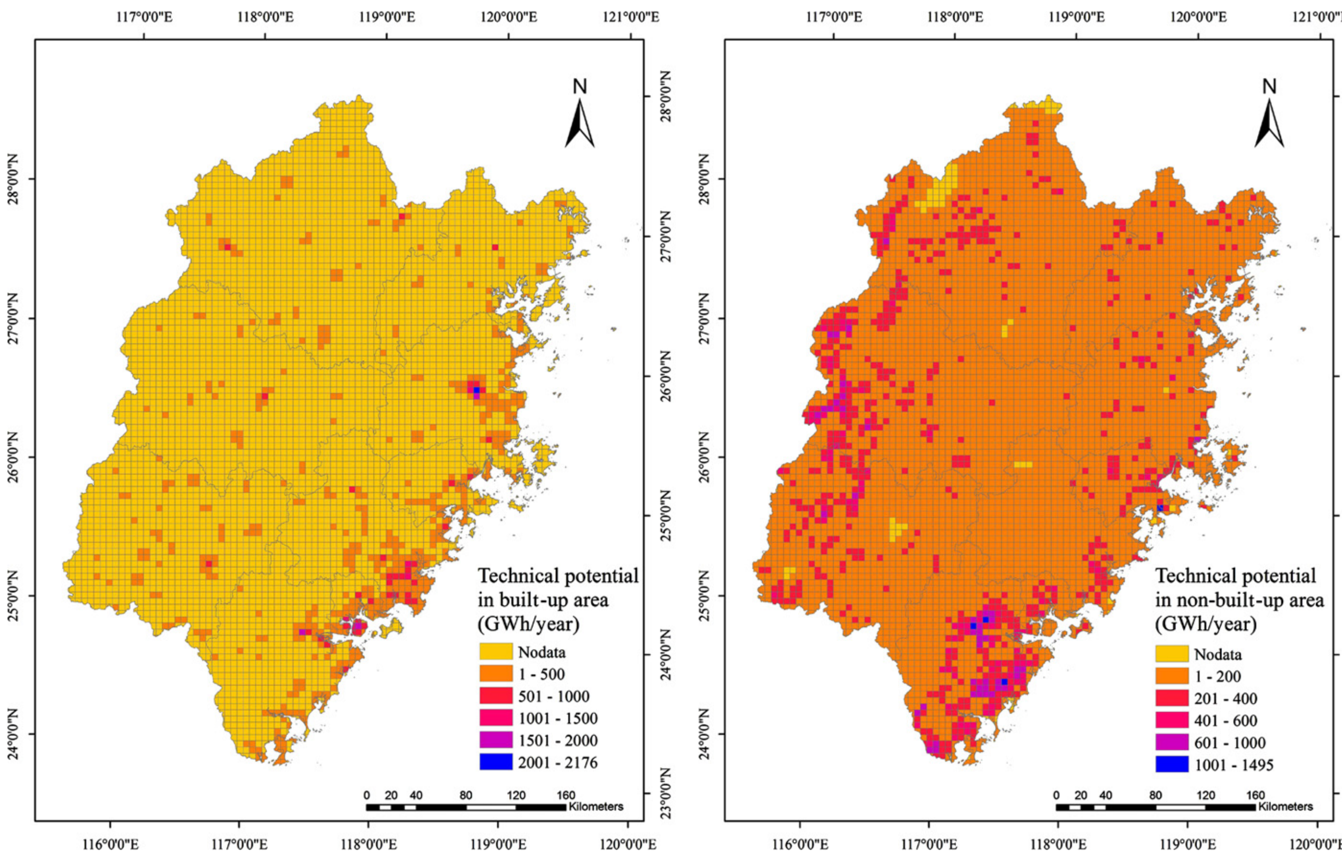

Fig. 5. Spatial distribution of technical potential in Fujian Province.

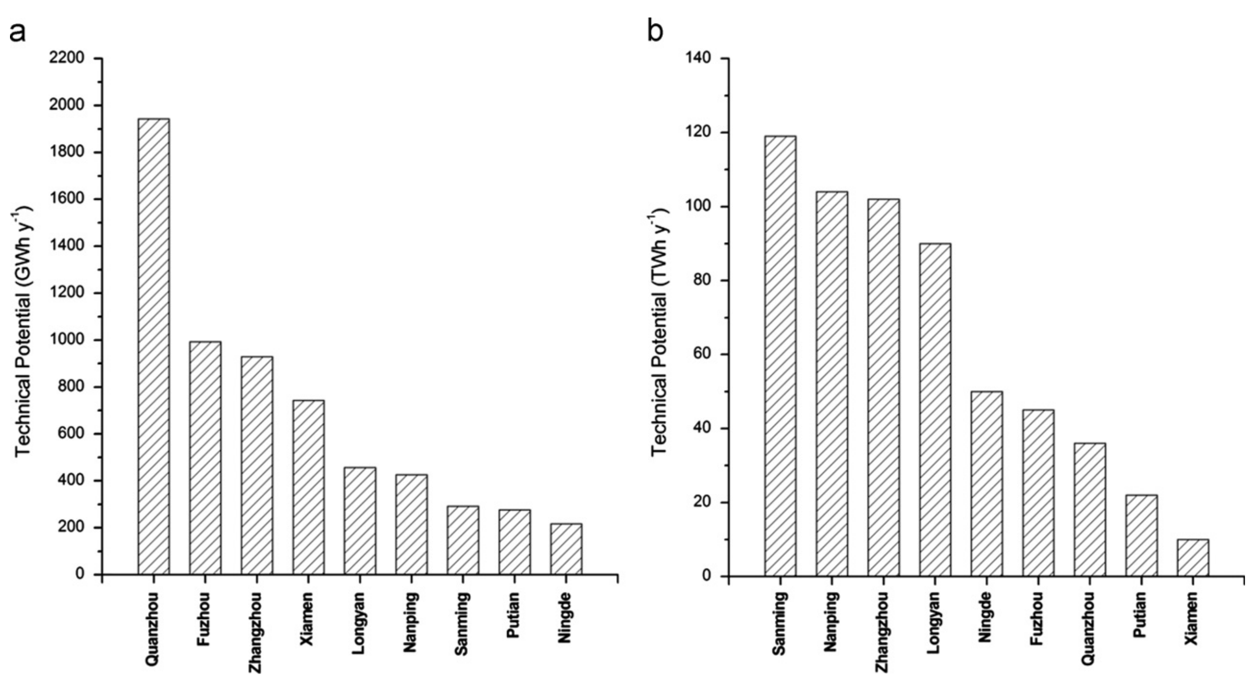

Fig. 6. The comparison of technical potential between nine preference-level cities in Fujian Province ((a) built-up area, (b) non-built-up area).

4.3. Technical potential

Fig. 5 shows the spatial distribution of annual PV electricity production on each grid unit for built-up and non-built-up area. The value on each grid unit represents the sum of cell values within the zones. The zonal statistics function in ArcGIS are using to summing over all grid cells within the administrative boundary of nine preference-level cities (shown in Fig. 6). The regional potential is estimated to be 586 TW h for the larger-scale PV plants in non-built-up area and 6.37 TW h for the roof-top PV plants in built-up area. The total amount of technical potential in Fujian Province is about 592.37 TW h, about 4–5 times the total electricity consumption (131.5 TW h) for Fujian Province in 2010.

Annual PV electricity production in a given region has close relations with climatic conditions, conversion efficiency of PV systems and total areas of suitable area. A similar geographical variation can be

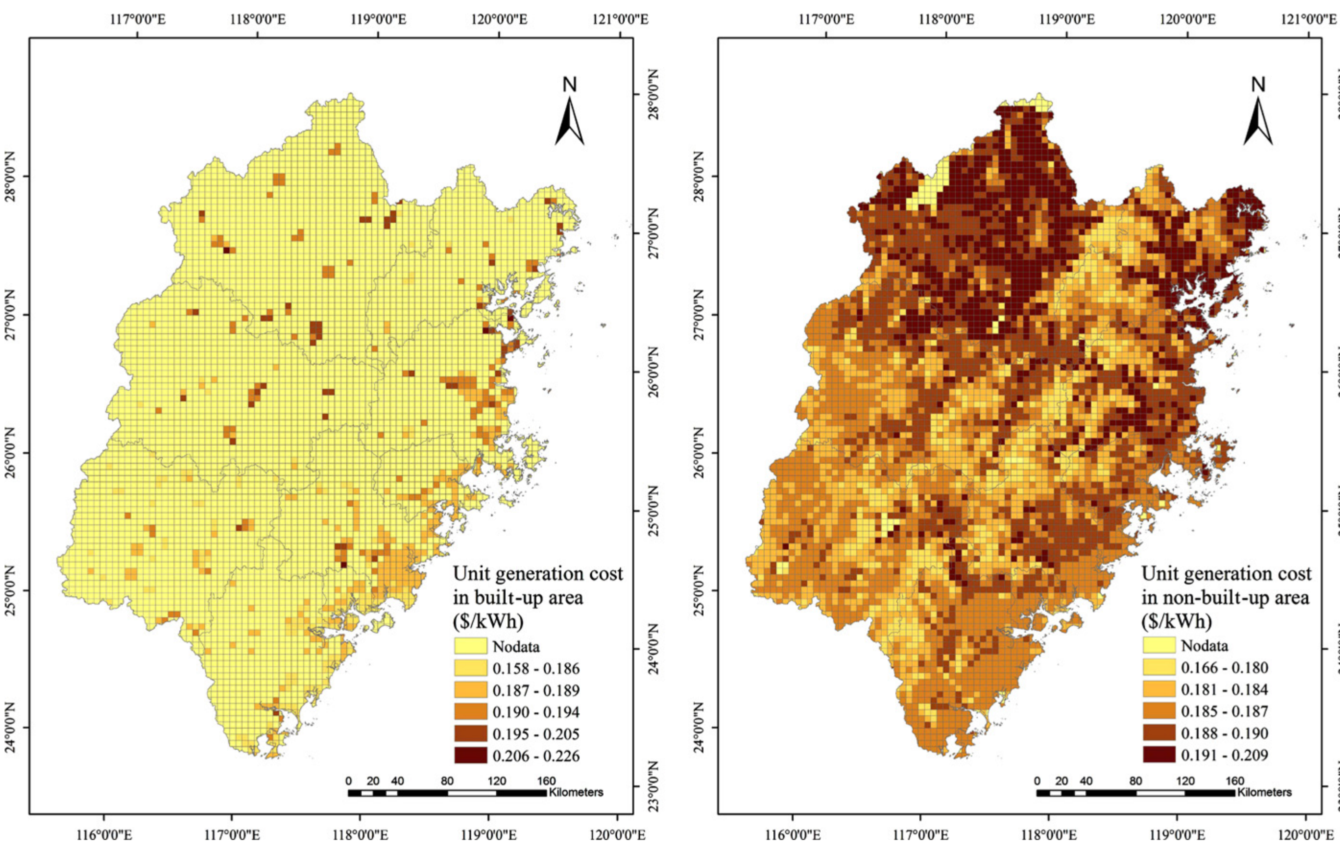

Fig. 7. Spatial distribution of PV electricity production cost for Fujian Province.

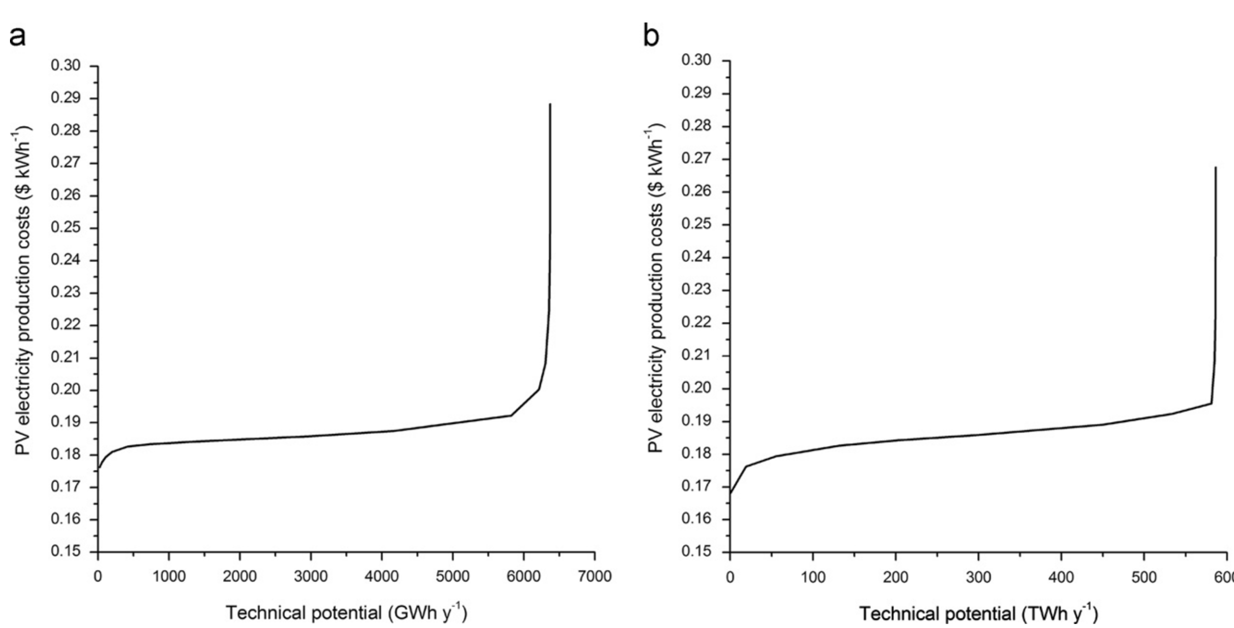

Fig. 8. Regional geospatial supply curves for solar energy ((a) built-up area, (b) non-built-up area).

observed for technical potential (Fig. 5). In absolute numbers (Fig. 6), the higher technical potential is found in Sanming, Nanping, Zhangzhou, with a large suitable area in non-built-up area; In built-up area, the most of PV generation production comes from Quanzhou, Zhangzhou, Fuzhou and Xiamen. This is duo to large amount of built-up area in these cities.

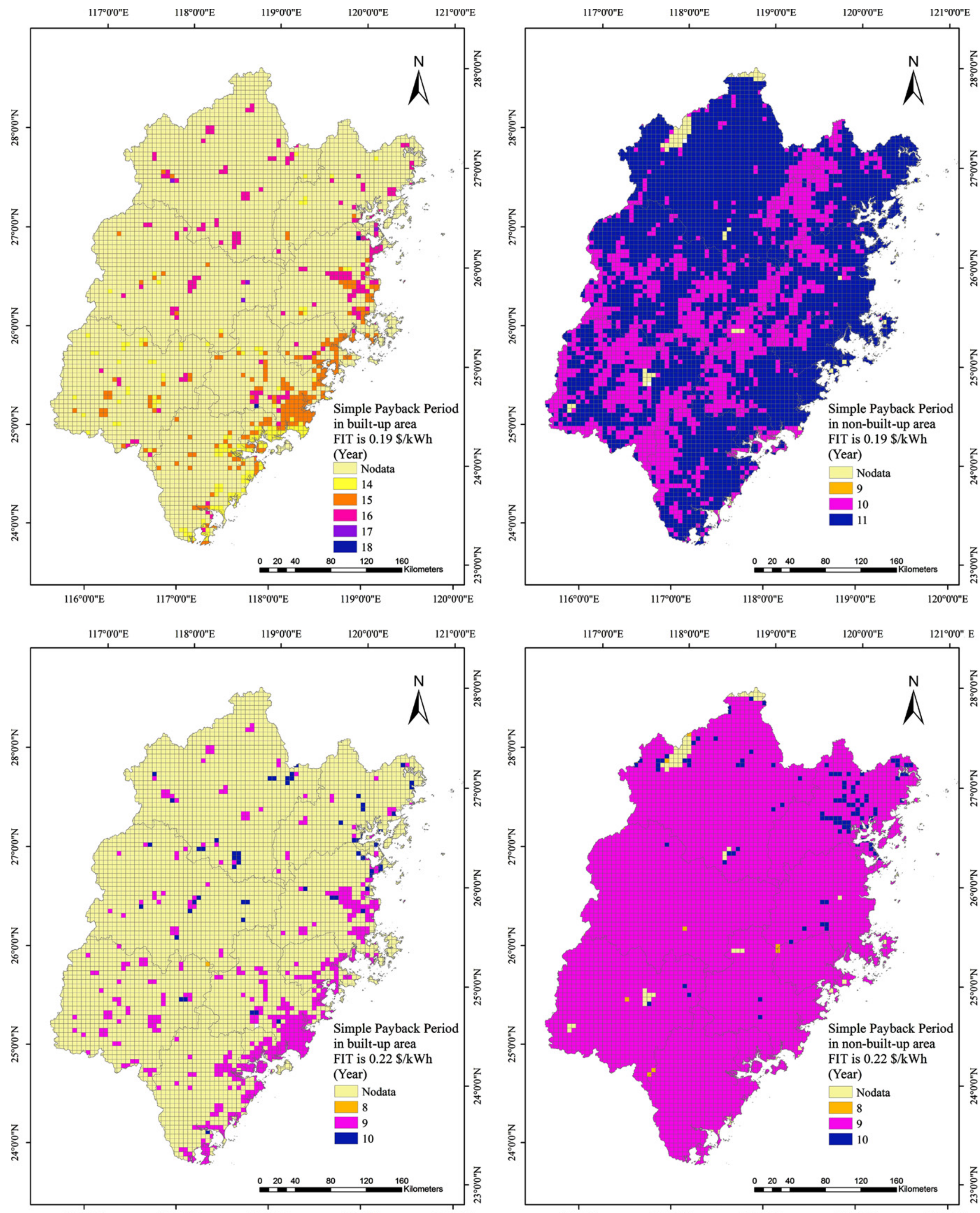

Fig. 9. Spatial distribution of SPP under two FIT scenarios for Fujian Province.

4.4. Economic potential

According to the cost model described in the previous section, the generation costs were calculated using reference PV system based on grid cell approach. The spatial distribution of PV production cost based on present price scenarios is illustrated in Fig. 7, and the value on each grid unit represents the average of cell values within the zones. Under present price level, the cost of PV generation ranges from 0.17 to 0.27 $/kW h in built-up area, and ranges from 0.16 to 0.27 $/kW h in non-built-up area, with average generation cost of 0.19 $/kW h. The

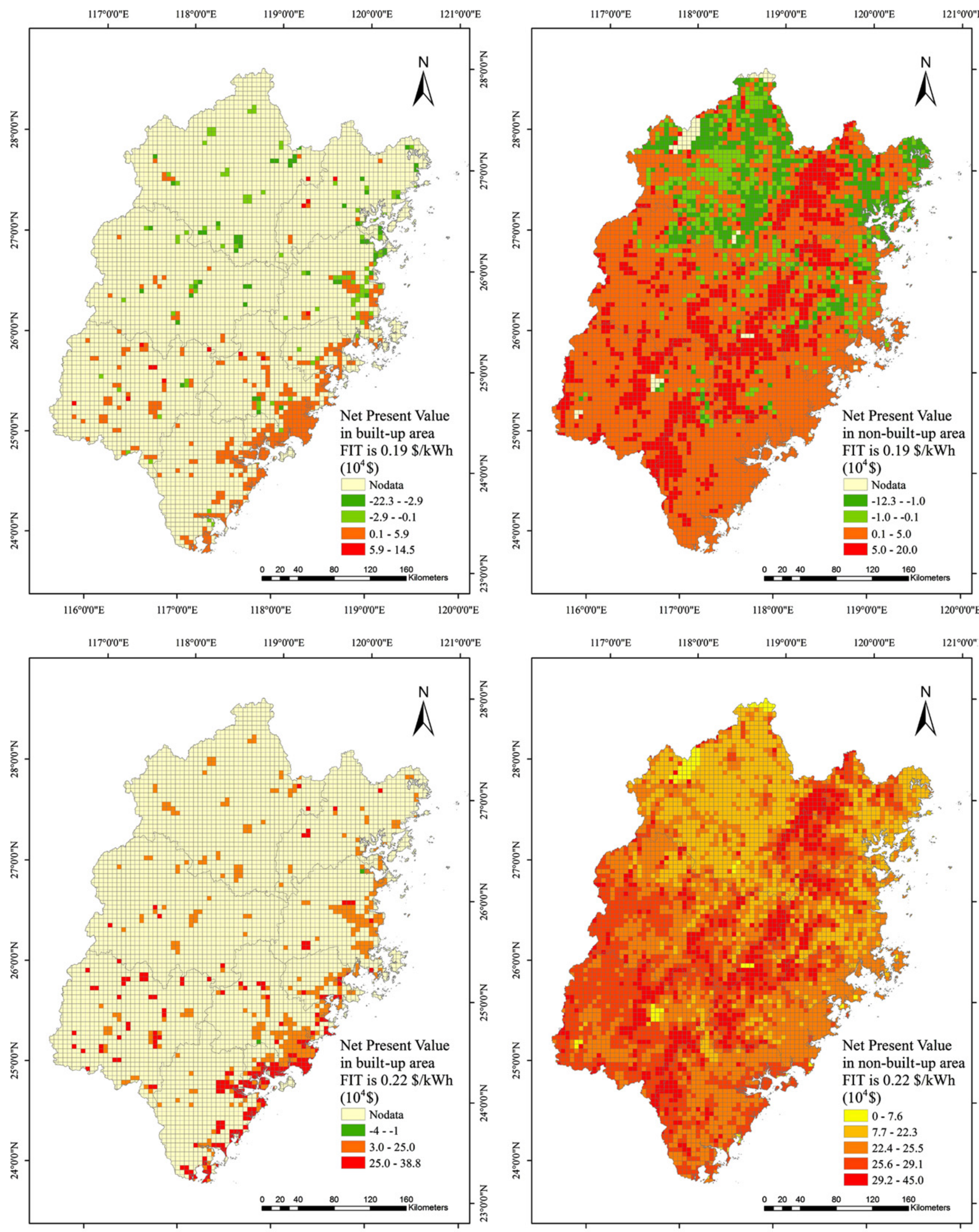

Fig. 10. Spatial distribution of NPV under two FIT scenarios for Fujian Province.

generation costs of PV are highly consistent with the solar radiation on each grid. The southeastern coastal region is the lower generation cost area for roof-top PV utility, including Zhangzhou, Xiamen, and Quanzhou (shown in Fig. 7). For non-built-up area, the lower generation cost for large-scale PV system can be seen in the central mountain area (generally, the generation cost is lower than 0.19 $/kW h).

The supply–cost curves of renewable-energy sources are an essential tool to synthesize and analyze large-scale energy-policy scenarios, both in the short and long terms. These curves allow for the assessment of economic potentials below a given price. The geospatial supply curves for Fujian Province are shown in Fig. 8. When the costs increase to 0.18 $/kW h for large-scale PV utility in non-built-up area, available electricity from PV can meet the present (2010) electricity consumption for Fujian Province. For roof-top PV utility in built-up area, when the cost increase to 0.21 $/kW h, it can provide electricity production of 6.3 TW h, about 5% of present (2010) electricity consumption for Fujian Province. The results illustrate that the economic potential is high if a reasonable FIT is set up.

4.5. Economic feasibility analysis for PV investment project

At present, the average tariff (mainly coal power) in Fujian is around 0.071 $/kW h (Price of Association of Fujian, 2012). According to the above cost analysis, the generation cost for solar energy is far higher than conventional energy. So the incentive policy is critical to promote the further development of solar energy. Though there is no fixed FIT for PV generation in China, two provinces have proposed a specific tariff: Shandong declared a progressive implementation curve (in 2010, 50 MW, in 2011, 80 MW, in 2012, 150 MW). The price from the FIT is of 0.27 $/kW h in 2010, 0.22 $ in 2011 and 0.19 $ in 2012. Jiangsu has a tariff similar to Shandong in 2011 for larger-scale PV plants. In this study, we assumed two FITs scenarios for Fujian Province: 0.19 and 0.22 $/kW h. The next step is to calculate the NPV and SPP on each grid cell. The spatial distribution of NPV and SPP are illustrated in Figs. 9 and 10, which can help investors to identify the region that have positive NPV with a acceptable level of finical risk. The value on each grid unit represents the average of cell values within the zones. The result implied that at a FIT of 0.19 $/kW h, solar could accommodate annual electricity as large as 5.11 TW h for built-up area, and 459.92 TW h for non-built-up area. It is about 3.5 times of the 2010 electricity consumption in Fujian Province. At the FIT of 0.22 $/kW h, more than 90% technical potential could have a positive NPV, with relatively short payback period.

4.6. CO_2 mitigation potential with solar energy

The regional CO_2 mitigation potential of PV is a very important reference indicator for energy planners to establish regional renewable energy planning. The PV system is a promising source of electricity generation for energy resource saving and CO_2 emission reduction (Sherwani et al., 2010). It has significant potential to deliver reduced CO_2 for large-scale application. To evaluate the potential of effective CO_2 reduction for PV utility in the study area, we calculated the indicator of alternative reduction of PV on each grid cell by the following equation:

$$R_i = (E_i - E_r) \times EF \tag{8}$$

where R_i is the annual alternative reduction by PV on grid cell i (tCO_2e/year), E_i is the annual energy yield in grid cells i (kW h/year), E_r is the annual energy consumption of PV system (kW h/year). According to research (Ito et al., 2008), the energy requirement of the VLS-PV systems range 30 to 42 TJ/MW, the PV-systems with mc-si module use 33.068 TJ/MW in the whole life time of PV system. EF is the baseline emission factors for east China power grids (Baseline Emission Factors for Regional Power Grids in China, 2010) (=0.76905 tCO_2e/MW h).

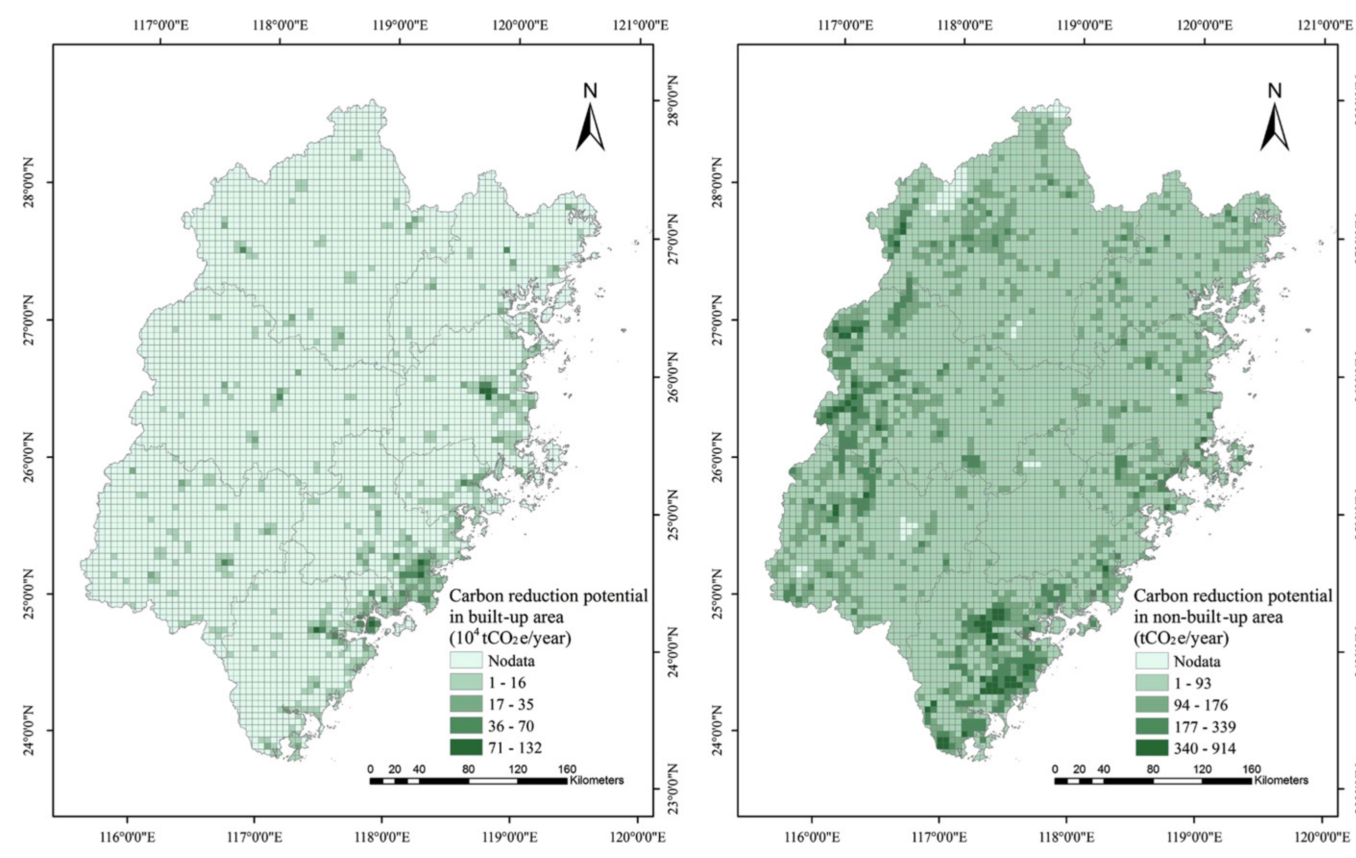

Fig. 11. Spatial distribution of annual CO_2 mitigation potential for PV.

Total CO_2 emission in Fujian is about 2300 million tonnes in 2010, and about 1/3 comes from electricity sectors (Zhao, 2012). With the method mentioned above, the annual CO_2 mitigation potential for PV generation can be assessed in the study area (Fig. 11). The value on each grid unit represents the average of cell values within the zones. The results of this research indicate a possibility of reducing CO_2 emissions in non-built-up area is about 3500 million tonnes per year, and about 3.8 million tonnes per year in built-up area, equivalent to around 1.5 times of total CO_2 emission in Fujian in 2010.

4.7. Sensitivity analysis

Uncertainty is often involved in multi-criteria decision making due to many different reasons such as the inability for decision-makers to provide precise input data. The uncertainty may lead to the imprecision of end results. Sensitivity analysis is often used to deal with this uncertainty and to quantify the effects of each input on modeling results. In this study, one-at-a-time sensitivity analysis was conducted to investigate the relative impacts of the input parameters of assessment model on the energy outputs.

In Eq. (2), the performance ratio of PV system (η_T) is a key input parameter for estimation of PV technical potential, and its value generally ranges between 0.7 and 0.85. As shown in Fig. 12, the relationship between performance ratio and total of technical potential is close to linear ($R^2=0.996$). When the performance ratio is increased with 1%, a total of technical potential would increase with 85 GW h/year.

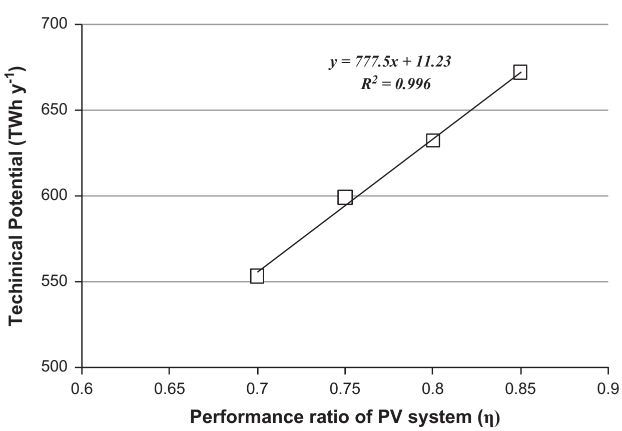

Fig. 12. Sensitivity of total technical potential to the performance ratio of PV system.

For the roof-top solar PV potential in the built-up area, the ratio between the area of roof-top and the total area of built-up (δ) and popularizing ratio of roof-mounted PV system (α) are also the key input parameters for estimation of PV technical potential. As shown in Fig. 13, the relationships between the ratio of δ, α and total of technical potential are also linear. When the ratio of δ is increased with 1%, the total of roof-top solar PV potential would increase with 318 GW h/year, while when the ratio of α is increased with 1%, the total of roof-top solar PV potential would increase with 212 GW h/year. Obviously, the roof-top solar PV potential are more sensitive to the ratio of δ.

The sensitive analysis results indicated that the total technical potential are significantly affected by the improvement of performance ratio of PV system. In addition, raising the ratios of δ, α can lead to greatly increase of the roof-top solar PV potential in the built-up area, especially for the ratio of δ.

5. Conclusions

This paper presented a computational procedure to derive a regional model of solar PV generation potential and its economic feasibility with the aid of the solar radiation analysis tool and map algebra functionality in the ArcGIS software. The work is innovative in integrating the physical and economical variables for a feasibility analysis on the regional scale. Meanwhile, numerous geographical factors, technology and cost data as well as the policy scenarios have been taken into account. This framework should be used by policy makers, investors, and maximum utilities of solar energy.

The application of the methodology in the case study showed that very high technical potential of PV electricity generation is available in Fujian Province. Spatial variability of PV energy output is larger, and it is highly correlated with the local solar energy resource. From the technical application point of view, decentralized roof-top PV systems should be the main solar energy utility in the coastal regions of Fujian, while the regions of Zhangzhou and interior west of Fujian are suitable to construct large-scale grid-connected PV power plants. The improvement the efficiency of PV power system and raising the popularizing ratio of building roof PV utility could greatly increase the total technical potential of solar energy.

The present unit cost of PV electricity generation is more than 0.16 \$/kW h, which is far higher than the average tariff of Fujian. So the solar energy development still depends on the energy policy and financial subsidies to the great extent. The main investment risks for project investors come from the absence of incentive mechanism like no fixed FIT for PV generation in China or Fujian. The results from economic feasibility analysis showed: when the

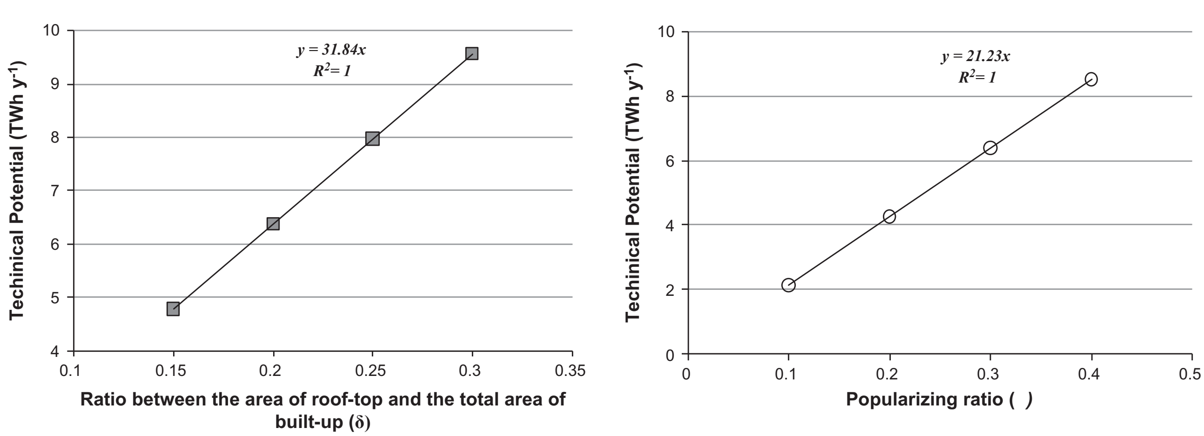

Fig. 13. Sensitivity of total technical potential to the ratio of δ and α in the built-up area.

FIT of PV electricity is assumed to be 0.19 $/kW h, the extent of suitable land for PV utility is large enough to cover the present total electricity consumption for Fujian Province. Based on this assumed FIT, investors of PV electricity projection could have a reasonable benefit for some regions which have high solar energy resource. Therefore, our study suggests that the FIT of 0.19 $/kW h is an appropriate subsidy level at this stage in order to achieve the goal of installing 100MWp of PV capacity by the end of 2015.

PV electricity also has the great potential to mitigate CO_2 emissions as an alternative energy of conventional energy. In these terms, the economic and environmental benefits of PV electricity are significant for Fujian Province. The cost of PV system is continuing to fall, but requires policy and program support to assist it in bridging the gap between financial and infrastructure resource, to build a sustainable PV industry sector.

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