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Research Article

Evaluation of Potential Geographic Distribution for Large-Scale Photovoltaic System in Suburbs of China

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Since China is the largest CO_2 emitting country in the world, photovoltaic (PV) systems are expected to be widely installed to reduce CO_2 emission. In general, available area for PV installation depends on urban area due to differences in land use and slope. Amount of electricity generated by a PV system also depends on urban area because of differences in solar irradiation and ambient temperature. The aim of this study is to evaluate the installation of large-scale PV systems in suburbs of China, taking these differences into consideration. We have used a geographic information system (GIS) to evaluate amounts of installation capacity of large-scale PV systems, electricity generated, and CO_2 emission reduction by the installation capacity of large-scale PV systems in suburbs of Liaoning, Shanghai, Anhui, and Guangdong. In Liaoning, the amount of CO_2 emission reduction by the installation capacity of large-scale PV systems was estimated to be the largest, 3,058 kt-CO_2/yr, due to its larger amount of the installation capacity, 2439.4 MW, than the amount of the installation capacity in other regions.

1. Introduction

According to the World Energy Outlook of IEA, the demand of annual primary energy in China is expected to be 3,737 Mtoe by 2035, about 1.8 times the energy consumption of China in 2008 [1]. In addition, China exhausts the most amount of CO_2 and has emitted 6877.2 Mt-CO_2 in 2009 [2]. Therefore, China has a large potential to reduce CO_2 emission in the Asian region, and the CO_2 emission reduction in China has an impact on the global warming.

The Chinese government currently focuses on renewable energy to reduce CO_2 emission. In the 12th Five Year Plan for Renewable Energy Development (2011–2015), the share of renewable forms of energy such as hydropower, wind, solar, and biomass is to be increased. Although the installed photovoltaic (PV) capacity was around 700 MW at the year-end 2010, and the State Council, China's national cabinet, has now raised the target for solar energy to an unprecedented level of 9 GW of PV installations by 2015 [3]. Thus, it is expected that large-scale PV systems will be widely installed in order to achieve this target.

There are few studies regarding installation of PV systems in China. Zhang et al. estimated cumulative installation of PV cells for large-scale PV power in China considering subsidy on PV installation and the electricity supply mix [4]. Ito et al. designed a very large-scale PV of 100 MW system in Gobi desert [5]. Byrne et al. assessed the economics and livelihoods impacts of stand-alone, small-scale PV system installation [6]. However, those studies give no explanation about potential of large-scale PV system based on the geographic feasibility analysis. In general, available area for a large-scale PV system depends on the specific urban area because of regional differences in land use, land slope, and the distance to the power-consuming area. The amount of electricity generated by a PV system also depends on the regional differences in solar irradiation and ambient temperature. Thus, the installation of large-scale PV systems should be evaluated for a specific region to account for these regional differences.

This study aims to estimate the geographical distribution of the available area for large-scale PV systems in China using the geographic information system (GIS). The GIS is an effective tool for the regional evaluation of the feasibility of the installation of large-scale PV systems and takes the regional differences into consideration. In this study, the available area for large-scale PV systems has been estimated.

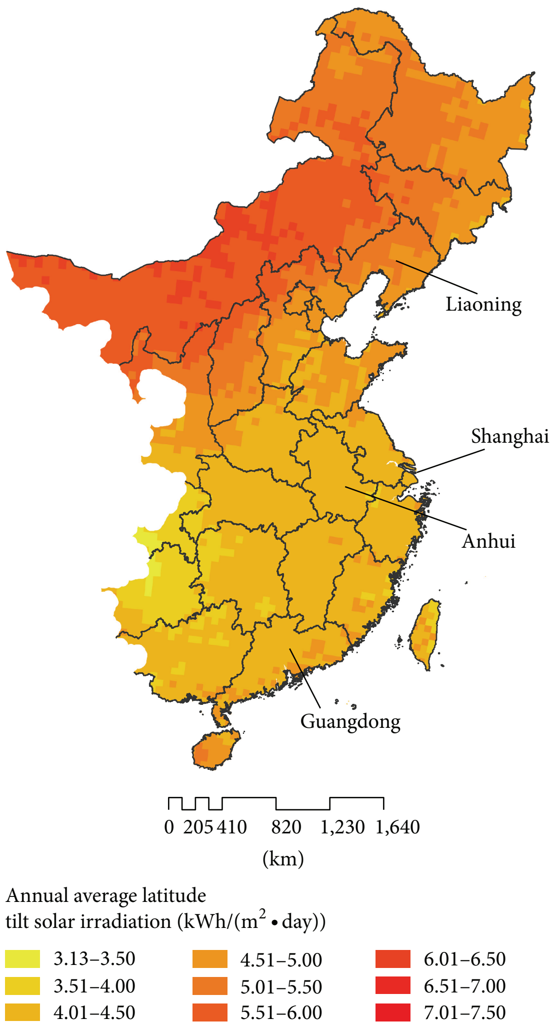

FIGURE 1: Distribution of tilt solar irradiation.

Thereafter, the installation capacity of the large-scale PV system, the electricity generated, and the CO_2 emission reduction is also evaluated. Finally, we have analyzed key-factors of the regional differences in CO_2 emission reduction.

2. Study Areas

First of all, distribution of tilt solar irradiation in China was clarified by using GIS data of Solar and Wind Energy Resource Assessment (SWERA) [7]. Figure 1 shows that the solar irradiation of coastal area in northeastern China is larger than that in southern or southeastern China. Four regions, Liaoning, Shanghai, Anhui, and Guangdong are considered as a subject area for study, because these regions are located on coastal area which is assumed to have a large number of urban area with strong demand for electrical power.

3. Methods

3.1. Estimation of Available Area for a Large-Scale PV System. For the installation of a large-scale PV system, an important

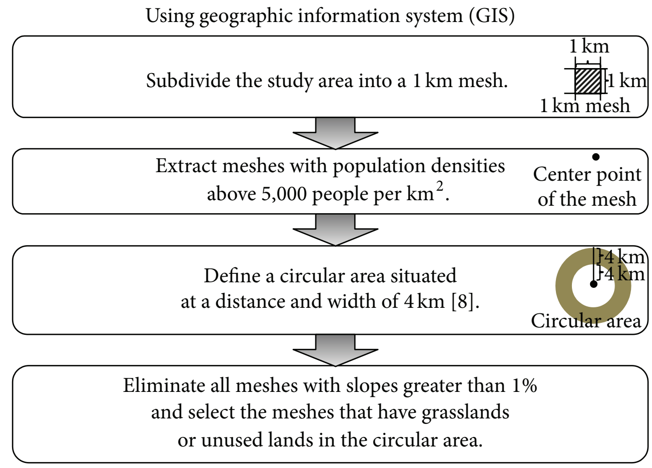

FIGURE 2: Steps of estimation of available area.

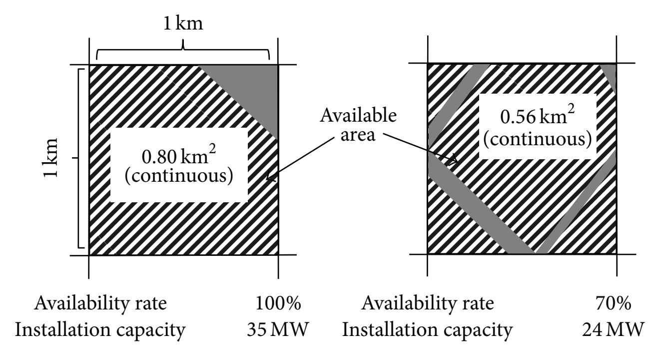

FIGURE 3: Samples of available area at availability rate (100%, 70%).

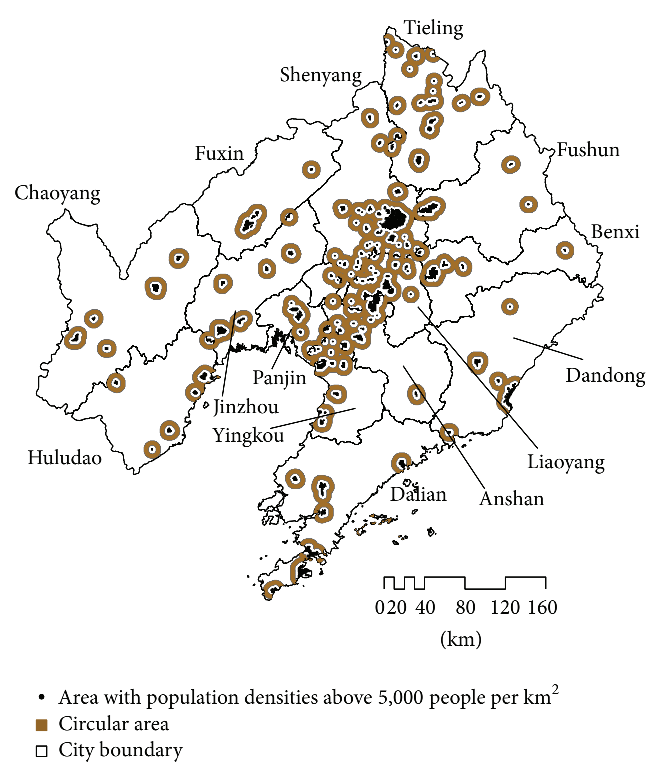

FIGURE 4: Distribution of the circular area in Liaoning.

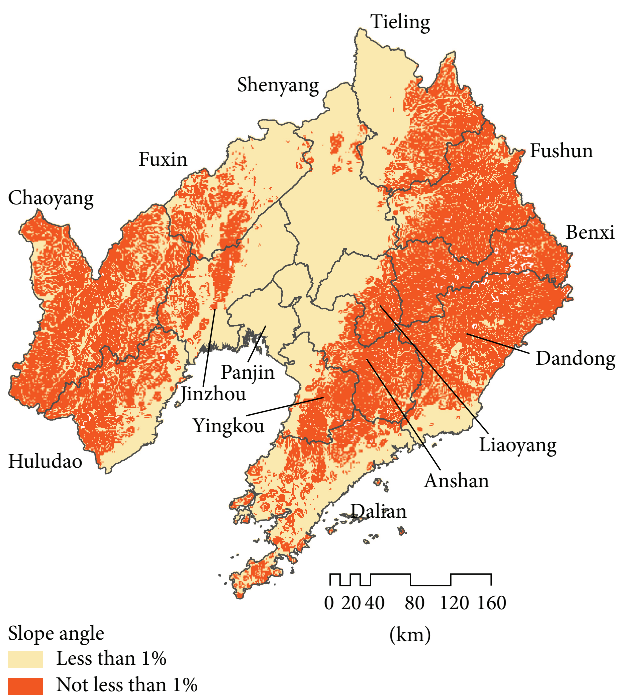

Figure 5: Distribution of slope angle in Liaoning.

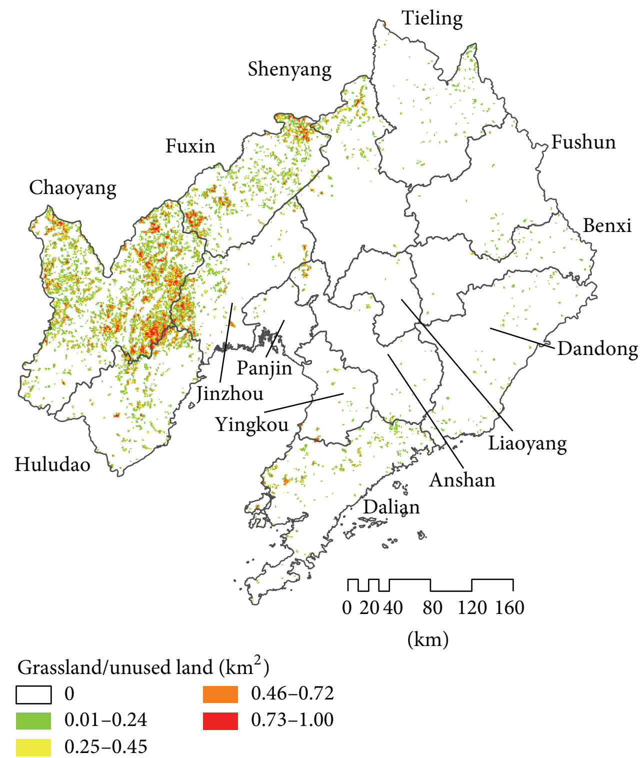

Figure 6: Distribution of grassland or unused land in Liaoning.

factor is the proximity to the power-consuming area. Land slope is also an important factor because it may drive up the construction costs of a large-scale PV system. Land use is a fundamentally important factor. Therefore, we defined the available area for a large-scale PV system as area that meets the following three requirements.

(1) A circular area situated at a distance and width of 4 km from the outer limits of area with population densities greater than 5,000 people per km^2 to the circumference of the circle (circular area) [8].

(2) Land sites with slopes less than 1%.

(3) Grassland and unused land.

Figure 2 shows steps of estimation of available area for a large-scale PV system. Using GIS, we first subdivided the study area into a 1 km mesh. Second, we extracted meshes with population densities above 5,000 people per km^2. Thereafter, we defined a circular area situated at a distance and width of 4 km from the outer limits of area with population densities greater than 5,000 people per km^2 to the circumference of the circle. We eliminated all meshes with slopes greater than 1%. Finally, we selected the meshes that have grassland or unused land. The population data for the meshes were obtained from population statistics data (2003) [9]. Land slope was obtained by analyzing a digital elevation model (DEM) data [10], using the GIS. The area of the grassland and unused land was obtained from the land use statistics data (2003) [9].

3.2. Estimation of Installation Capacity. Capacity larger than 20 MW PV systems is the subject of this study. Installation

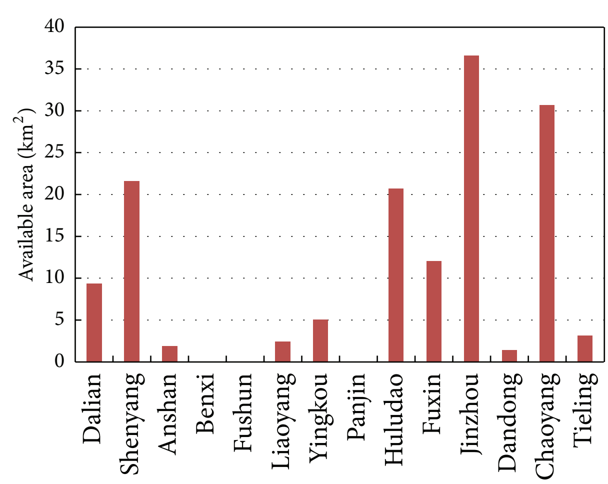

Figure 7: Available area for large-scale PV systems.

capacity for each region is estimated for each 1 km mesh. To estimate the installation capacity, we defined a PV capacity density of 44 MW/km^2 [11]. Multiplying this density by the available area on each 1 km mesh yields the installation capacity. Additionally, we defined availability rates from 10% to 100% for the available area, and we assumed that available area at each availability rate is continuous area that a large-scale PV system needs. We also estimated the installation capacity for each availability rate. Figure 3 shows samples of available area (0.80 km^2) at availability rate 100% and 70%. A shaded area on the left in Figure 3 shows an example of the available area at availability rate 100%, and the installation

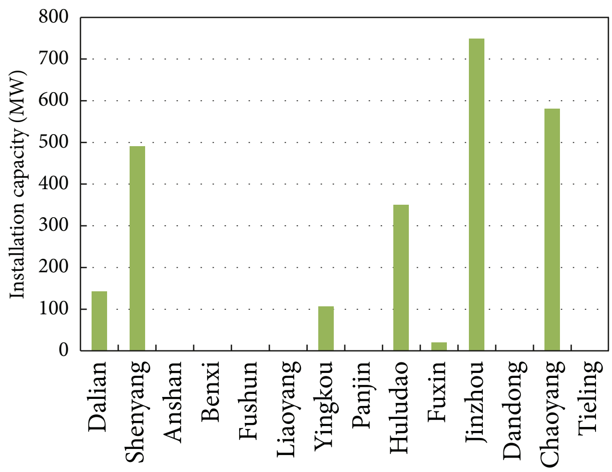

FIGURE 8: Installation capacity at availability rate 100% in each district in Liaoning.

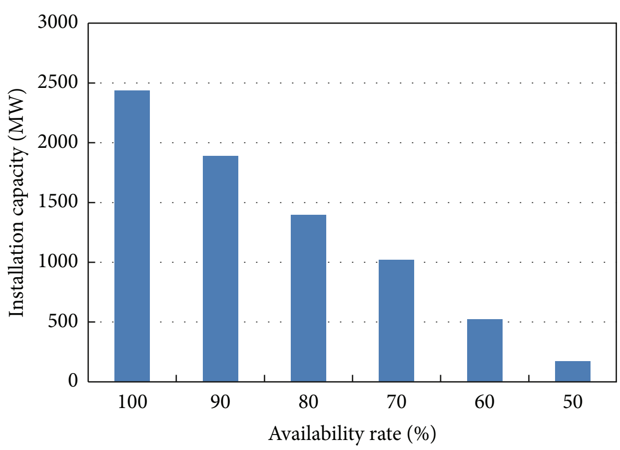

FIGURE 9: Installation capacity at each availability rate in Liaoning.

capacity in the mesh is estimated to be 35 MW because 100% of the available area (0.80 km^2) is assumed to be all continuous area. While a shaded area on the right in Figure 3 has also available area (0.80 km^2) in total, the installation capacity in the mesh is estimated to be 24 MW because 70% of the available area is assumed to be continuous area (0.56 km^2) at availability rate 70%.

3.3. Calculation of Electricity Generated by the PV System. The electricity generated annually by a PV system, E_{Py} (kWh), for each 1 km mesh is estimated from (1) [12] as

$$E_{Py} = \sum E_{Pm}, \tag{1}$$

where E_{Pm} [kWh] is the monthly energy generation for each 1 km mesh and is estimated from (2) [13] as

$$E_{Pm} = K \times P_{AS} \times \frac{H_{Am}}{G_S}, \tag{2}$$

where K is the performance ratio of the PV system, which is obtained from (3) [13]; P_{AS} (kW) is the nominal power of

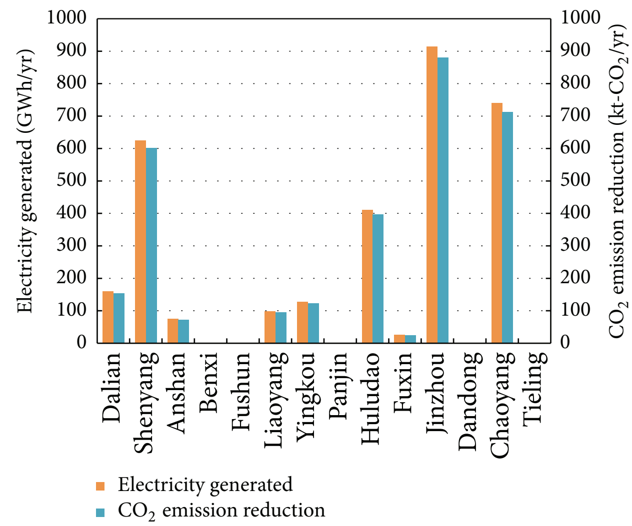

FIGURE 10: Total amounts of electricity generated and CO_2 emission reduction in each district of Liaoning.

the PV array under standard test conditions; H_{Am} (kWh/m^2· month) is the monthly total solar irradiation tilted at latitude on each 1 km mesh; G_S is the total irradiance under standard test conditions, which is 1.0 kW/m^2 [12]. H_{Am} is obtained from the GIS data on Solar and Wind Energy Resource Assessment (SWERA) [7] as

$$K = K_{HD} \times K_{PD} \times K_{PM} \times K_{PA} \times K_{PT} \times \eta_{INO}, \tag{3}$$

where K_{HD} is the parameter for losses on the PV array surface; K_{PD} for time-dependent losses by the module function; K_{PM} for losses by the array load; K_{PA} for losses by the array circuit. K_{PT} is the module temperature coefficient, which is obtained from (4). η_{INO} is the effective energy efficiency of the inverter. We use the JIS recommended values of 0.97 for K_{HD}, 0.95 for K_{PD}, 0.94 for K_{PM}, 0.97 for K_{PA}, 0.90 and for η_{INO} [13] as

$$K_{PT} = 1 + \alpha_{Pmax} \times \frac{(T_{CR} - 25)}{100}, \tag{4}$$

where α_{Pmax} is the maximum power temperature coefficient, which is $-0.41^{\circ}C^{-1}$ for c-Si PV modules; T_{CR} (°C) is the temperature of the PV module, which is obtained from (5) [13] as

$$T_{CR} = T_{AV} + \Delta T, \tag{5}$$

where T_{AV} (°C) is the daily ambient temperature profile averaged over month; ΔT (°C) is the weighted average of the annual increase of module temperature. We obtained T_{AV} for that region from the World Surface Data (2009) [14]. We used a value of 18.4°C for ΔT for PV systems mounted on racks [13].

3.4. Calculation of CO_2 Emission Reduction. Annual CO_2 emission reduction, ER_{CO_2} [t-CO_2/yr], by the PV system is obtained from following equation:

$$ER_{CO_2} = RF_{CO_2} \times EG, \tag{6}$$

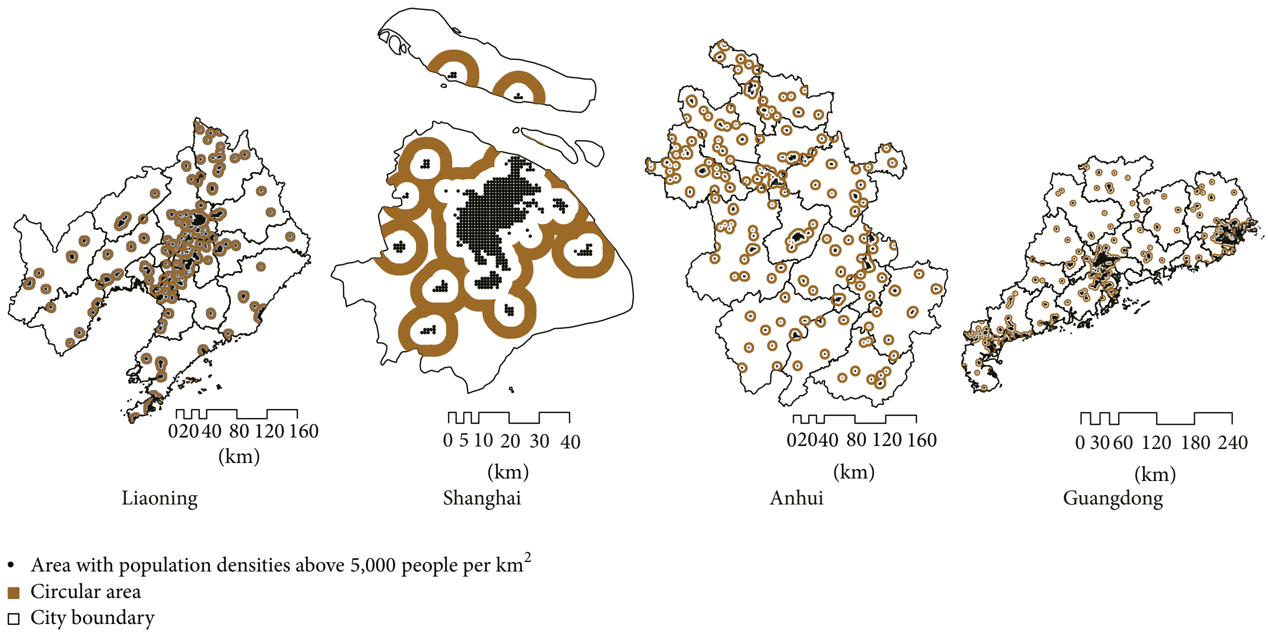

Figure 11: Distribution of the circular area in each region.

Table 1: Value of RF_{CO_2} for each region.

Region	Power grid	RF_{CO_2} (t-CO_2/MWh)
Liaoning	Northeast	0.9635
Shanghai and Anhui	East	0.7931
Guangdong	Southern	0.7906

where RF_{CO_2} (t-CO_2/MWh) is the CO_2 emission reduction factor. EG (MWh/yr) is the electricity generated annually by the PV system. We used the baseline emission factor, EF, from the Clean Development Mechanism (CDM) for PV installation projects as the value for RF_{CO_2}. The values of RF_{CO_2} differ depending on power grid and are listed in Table 1. The EF for each region is obtained using the "Consolidate methodology for grid-connected electricity generation from renewable sources" [16] and using the following equation with values of operating margin CO_2 emission factor, EF_{OM}, Build Margin CO_2 emission factor, EF_{BM}, weighting of operating margin emission factor, $w_{OM} = 0.75$, weighting of build margin emission factor, $w_{BM} = 0.25$ [17, 18]:

$$EF = EF_{OM} \times w_{OM} + EF_{BM} \times w_{BM}. \quad (7)$$

4. Results and Discussion

In this chapter, detailed results for Liaoning are shown and discussed first. Next, results for Shanghai, Anhui, and Guangdong are shown and we finally discuss the regional differences by comparing each result.

4.1. Results for Liaoning

4.1.1. Available Area for Large-Scale PV Systems. Figure 4 shows the circular area situated at a distance and width of 4 km from the outer limits of area with population densities greater than 5,000 people per km^2 to the circumference of the circle in Liaoning. It is shown that the large number of circular area is located in the central district of Liaoning. Figures 5 and 6 show the distribution of slope angle and grassland, unused land in Liaoning, respectively. From Figure 5, it is found that most of central district of Liaoning has the land with slope angle less than 1%. It is shown from Figure 6 that the large amount of area with grassland or unused land is located in the western districts of Liaoning.

Figure 7 shows the available area for large-scale PV systems in each district of Liaoning. Jinzhou has the largest available area, 36.6 km^2, because it has a large amount of grassland or unused land with slopes less than 1%. Shenyang, Huludao, and Chaoyang also have larger available area as compared to the other districts, because there are large areas of grassland and unused land. On the other hand, Benxi and Fushun have very little available area because of their small amount of the circular area with slope less than 1% and with grassland or unused land. Panjin has no available area despite all land in its circular area with slope less than 1%. The total available area for installation is estimated to be 144.74 km^2 in Liaoning.

4.1.2. Installation Capacity of a Large-Scale PV System. Figure 8 shows the installation capacity of a large-scale PV system at availability rate 100% in each district of Liaoning. The districts with the largest available area have the largest amount of installation capacity. Jinzhou is estimated to have the largest installation capacity of 749 MW at availability rate 100%. A PV system larger than 20 MW cannot be installed in Benxi, Fushun, Tieling, Dandong, and Panjin.

Figure 9 shows the total installation capacity in Liaoning at availability rates from 50% to 100%. Installation capacity has not been derived for availability rates from 10% to

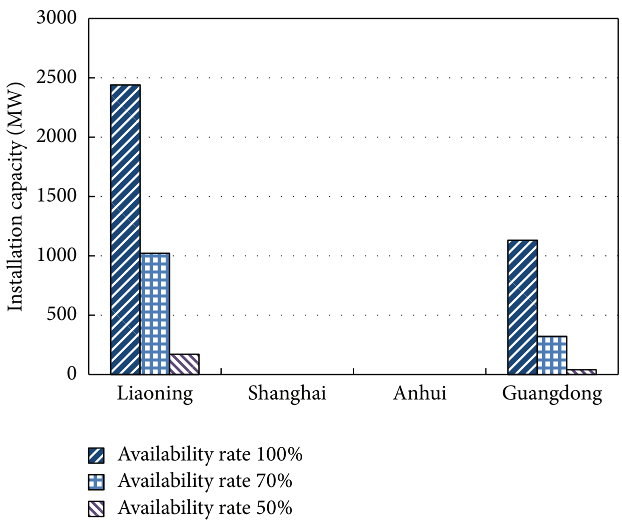

Figure 12: Installation capacity at each availability rate (50%, 70%, and 100%) in each region.

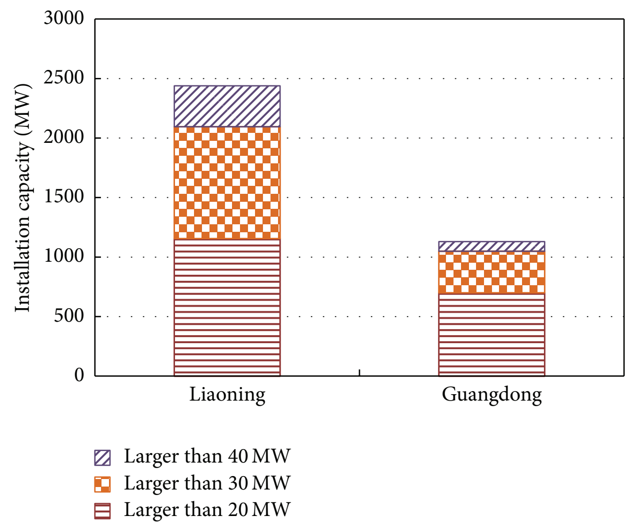

Figure 13: Scale of installation capacity at availability rate 100%.

40%, because a PV system larger than 20 MW needs more than 0.46 km^2 for installation. The total installation capacity in Liaoning is estimated to be 2,439.4 MW. This value is equivalent to 10.4% of the maximum power demand of 23,940 MW [19]. At lower availability rates of 70% and 50%, the installation capacity in Liaoning is estimated to be 1,021.0 MW, and 171.8 MW respectively. The installation capacity at lower rates is more likely installed, because the area margin is more sufficiently accounted for.

4.1.3. Electricity Generated and CO_2 Emission Reduction. Figure 10 shows the total amounts of electricity generated and CO_2 emission reduction by installation capacity at availability rate 100% in each district of Liaoning. Jinzhou has the largest amount of electricity generated, 913.5 GWh/yr, and CO_2 emission reduction, 880.2 kt-CO_2/yr.

Benxi, Fushun, Panjin, Dangdong, and Teiling are estimated to have no electricity generated and CO_2 emission reduction. These values mainly depend on the difference in installation capacity because there is little difference in solar irradiation and ambient temperature between districts and also the reduction emission factor, RF_{CO_2}, is a constant value with regard to each district.

4.2. Comparison of the Results Between Different Regions

4.2.1. Comparison of the Available Area and Installation Capacity. Figure 11 shows the circular area situated at a distance and width of 4 km from the outer limits of area with population densities greater than 5,000 people per km^2 to the circumference of the circle in each region. The total amount of circular area and the available area for large-scale PV systems in each region are shown in Table 2. Liaoning has the largest amount of the available area because it has a lot of the circular area that have a large amount of grasslands or unused lands with slopes less than 1%. While Anhui and Guangdong have larger amount of the circular area than that of Liaoning, the available area of Anhui and Guangdong is smaller than that of Liaoning. The reason is that Anhui and Guangdong has smaller grassland or unused land in a lot of circular area. Shanghai has no available area, since it has smaller amount of circular area and there are no grassland or unused land in its circular area.

Figure 12 shows the installation capacity of a large-scale PV system at availability rates (50%, 70%, and 100%) in each region. For each availability rate, a PV system lager than 20 MW cannot be installed in Shanghai and Anhui. At availability rate of 100%, Liaoning is estimated to have a capacity of 2,439.4 MW, which is the largest installation capacity. The installation capacity in Guangdong is estimated to be 1,131.2 MW. At lower availability rates 70% and 50%, the installation capacity in Liaoning is estimated to be 1,021.0 MW and 171.82 MW, respectively. In Guangdong, the installation capacity is estimated to be 321.6 MW and 40.7 MW, respectively.

Table 3 lists the ratio between installation capacity at availability rates of 100% and peak demand for electricity in each region. The installation capacity in Liaoning, 2,439.4 MW, is equivalent to 10.4% of the peak demand 23,470 MW [19]. The installation capacity in Guangdong is equivalent to 1.5% of its peak demand 74,540 MW [20]. The ratio between installation capacity and peak demand of Shanghai and Anhui is equivalent to 0% since each region has no installation capacity.

Figure 13 shows the amount of installation capacity for each scale (larger than 20 MW or 30 MW or 40 MW) at availability rate of 100% in Liaoning and Guangdong. In Liaoning, the installation capacity in case of larger than 30 MW amounts to 52.6% of its total capacity, which is higher than Guangdong. Liaoning has much continuous available area. Thus, it is supposed that large scale PV system is able to be installed in Liaoning.

4.2.2. Comparison of the Electricity Generated and CO_2 Emission Reduction. Table 4 lists annual electricity generated in

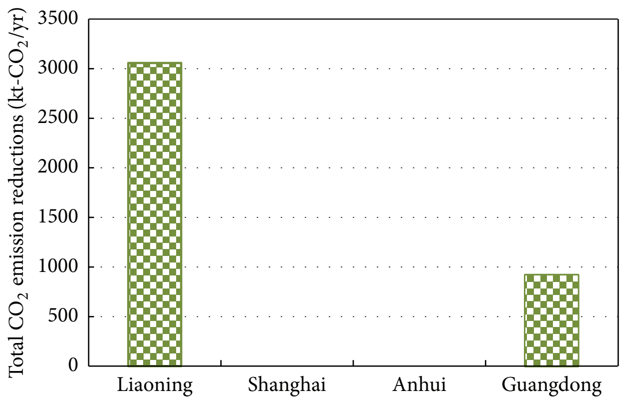

Figure 14: Total CO_2 emission reduction in each region.

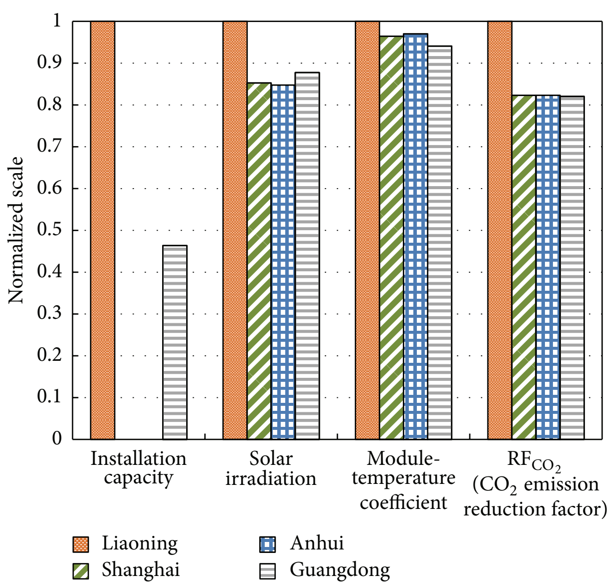

Figure 15: Overall comparisons on a normalized scale.

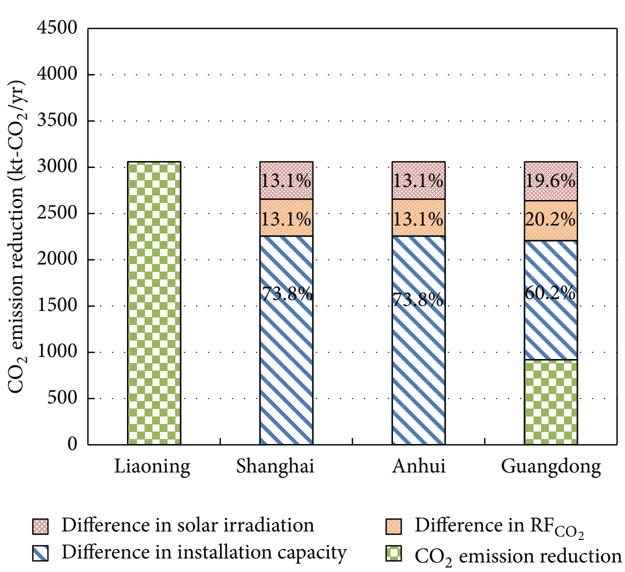

Figure 16: Details of the differences in the total amount of CO_2 emission reduction in each region.

Table 2: Total circular area and available area.

Region	Liaoning	Shanghai	Anhui	Guangdong
Circular area (km^2)	16,452	1,653	22,441	19,333
Available area (km^2)	144.7	0	0.6	77.9

Table 3: Ratio between installation capacity at availability rate 100% and peak demand in each region.

Region	Liaoning	Shanghai	Anhui	Guangdong
Installation capacity (MW) (Availability rate 100%)	2,439.4	0	0	1,131.2
Ratio between installation capacity and peak demand (%)	10.4	0	0	1.5

Table 4: Comparison of electricity generated in each region (GWh/yr).

Region	Liaoning	Shanghai	Anhui	Guangdong
Total electricity generated (2010) [15]	134,000	94,400	146,300	314,600
Total electricity generated by installation capacity of PV systems	3,174	0	0	1,162

2010 and by installation capacity of large-scale PV system in each region. In Liaoning, the total electricity generated by the installation capacity of large-scale PV system at availability rate 100% is estimated to be 3,174 GWh/yr which is equivalent to 2.4% of its total electricity generated in 2010 [15]. In Guangdong, the total electricity generated by installation capacity of large-scale PV system at availability rate 100% is estimated to be 1,162 GWh/yr which is equivalent to 0.4% of its total electricity generated in Guangdong in 2010 [15].

Figure 14 shows the total CO_2 emission reductions by the total electricity generated by installation capacity of large-scale PV system at availability rate 100%. The amount of total CO_2 emission reduction is estimated to be 3,058 kt-CO_2/yr in Liaoning and 919 kt-CO_2/yr in Guangdong.

4.2.3. Key-Factor Analysis. Figure 15 shows a comparison of the CO_2 emission reduction in each region on a common normalized scale ranging from 0 to 1 on the basis of the following factors, namely, the installation capacity at availability rate of 100%, the solar irradiation, the module-temperature coefficient, and the RF_{CO_2}. This method makes it simpler to compare the results of this study, since 1 represents the best and 0 represents the worst for each factor. From the figure, the difference in the total CO_2 emission reduction is affected significantly by the difference in the installation capacity. The difference in the module-temperature coefficient has little effect on the differences in CO_2 emission reduction.

Differences in RF_{CO_2} mainly affect the CO_2 emission reduction from a 20 MW PV system, since differences in the total installation capacity are unrelated. In this case, RF_{CO_2}

has more influence on CO_2 emission reduction than solar irradiation between Liaoning and the other regions.

Figure 16 shows the key-factor analysis with normalization and the following are the details of the differences in the total amount of CO_2 emission reduction between Liaoning and the other regions. Between Liaoning and Shanghai or Anhui, the installation capacity occupies 73.8%, and the difference in the solar irradiation including the module-temperature coefficient and the RF_{CO_2} is 13.1%. Between Liaoning and Guangdong, the installation capacity occupies 60.2%, and the difference in the solar irradiation including the module-temperature coefficient and the RF_{CO_2} is 19.6% and 20.2%, respectively.

5. Conclusions

The present study shows the installation capacity of large-scale PV systems, electricity generated, and CO_2 emission reduction by the installation capacity of PV system in Liaoning, Shanghai, Anhui, and Guangdong considering regional differences.

The installation capacity of large-scale PV systems in Liaoning is estimated to be largest because its available area, namely, the grassland and unused land, for large-scale PV systems is larger than the other regions. The amount of total electricity generated and CO_2 emission reduction by the installation capacity in Liaoning is more 2.7 times larger than the other regions.

From the results obtained by key-factor analysis, the total CO_2 emission reduction is affected by three factors, significantly by the difference in the installation capacity. The difference in the installation capacity is more than 3 times larger than that in solar irradiation and RF_{CO_2}. The difference in the CO_2 emission reduction factor is not negligible between Liaoning and Guangdong because it is 20.2%. Based on the results of the evaluations performed in this study, it is expected that CO_2 emission reduction by installing large-scale PV system will be larger in the region that has larger installation capacity.

Acknowledgment

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