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A GIS-based high spatial resolution assessment of large-scale PV generation potential in China

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HIGHLIGHTS

- 600 land conversion factors are used to estimate the large-scale PV potential.
- The potential PV power generation in China is estimated to be 1.38874×10^{14} kWh.
- China's eight developed coastal provinces account for 1% of generation potential.
- Associated CO_2 reduction could meet China's emission reduction commitment.
- Maximum PV scenario needs inter-regional transmission capacity reach 300 GW.

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ABSTRACT

The achievement of temperature control target requires a low carbon transition of global energy structure. While China is actively promoting the implementation of large-scale PV generation technology, there is still a lack of scientific knowledge of the generation potential in China. To address this deficiency, this study builds a GIS-based model with 600 land conversion factors incorporated to accurately estimate the large-scale PV power generation potential in China. The results show a potential installed capacity of 1.41×10^5 GW, corresponding to an annual power generation of 1.38874×10^{14} kWh or 21.4 times national electricity consumption in China 2016. If this potential were fully realized as a replacement for current fossil fuel-based power generation in China 2030, a reduction in China's carbon intensity of 63–68% compared to 2005 would result, which is sufficient to meet China's CO_2 emission reduction commitment. On a provincial level, while generation potential in Northwest and Inner Mongolia together account for 86% of the total, China's eight economically developed coastal provinces only account for 1%. To achieve a maximum large-scale PV scenario in China 2030, the capacity of inter-regional transmission grids from Northwest region and Inner Mongolia to the regions with insufficient potential should reach an approximate 300 GW. Our study could provide decision-makers with the precise information on large-scale PV power generation map of China, and optimizing low carbon strategies and inter-regional power transmission for achieving sustainable development.

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1. Introduction

2015 Paris Agreement set the temperature control target to mitigate global climate change [1]. As the world's largest carbon emitter, China made a voluntary emission reduction commitment that in 2030 the national carbon intensity (adjusted GDP) would reduce by 60–65% compared to 2005. The fulfillment of the commitment is unseparated from the development of clean energy generation given that fact that approximate 40% of China's energy-related CO_2 emissions comes from power sector. With ambitions development plans on renewable energy actively implemented by Chinese government these years, China has already become the global PV industry leader [2]. By the end of 2017, China's total installed PV capacity reached 131.1 GW, accounting for 32.6% of global installed capacity and surpassing the government's target for 2020 by a large margin [3]. Most of the increase in capacity in China leading up to the end of 2017 was attributed to large-scale PV projects. The importance of developing large-scale PV has also been emphasized in the National Renewable Energy Development Plan [4]. While China's National Development and Reform Commission has decided to reduce or cancel subsidies for PV projects since May 2018 [5], which has already resulted in a decreased growth rate of PV installed capacity during third quarter of 2018 [6]. It would not reverse the overall upward trend and could create opportunities for further marketization of the PV industry.

PV generating technology has been of interest to China because solar resources is abundant and the technology can reduce carbon emissions as compared to fossil fuel-based power generation from a life cycle perspective [7], which would contribute to the realization of China's carbon intensity reduction commitments and the IPCC's temperature control target [8]. The CMA Wind and Solar Energy Resources Center has found that China's land surface can receive up to 5.28×10^{16} MJ of solar radiation [9], which is 401 times of China's national energy demand in 2017. However, the implementable power potential from these solar resources is subject to geographical and technical constraints. Potential of solar generation can be classified into geographical potential and generation potential. Geographical potential of solar generation in a chosen area is defined as the amount of the total yearly solar radiation available in that area taking into account existing geographical constraints [10]. Generation potential of solar generation in a chosen area is defined as the certain amount of geographical potential in that area that can be actually converted into electricity given the available solar power technologies [10]. The Geographical Information System (GIS) has emerged as a powerful tool for calculating spatial renewable energy potentials.

To find the geographical potential for solar power technologies, many studies first exclude areas which are unsuitable for power plant installations like protected areas as well as water bodies, and then choose the most suitable areas based on the availability of solar resources. Clifton et al. [11] assessed the CSP (concentrated solar power) potential in a rural area of Western Australia (Wheatbelt region) with various spatial factors considered. In order to more accurately identify the most suitable areas for PV installations, the analytical hierarchy process (AHP) is widely used to locate PV hot spots. AHP is a mathematical approach which could realize the integration of different geographical constraints based on numerical weights assigned to them. Merrouni et al. [12] combined GIS and AHP to find the sites in the eastern region of Morocco highly suitable for PV. Aly [13] used the same method to identify PV hot spots in the country of Tanzania, but using two kinds of numerical weights for geographical constraints during their AHP process based on two different scenarios thus making the assessment results more comprehensive. In China, Liu et al. [14] performed site selection of PV power plant in four cities based on eight decision-making criteria in Northwest China. These studies successfully identified the distribution of geographical potential in studied areas according to the level of solar resource availability. However, they did not quantify the size of PV generation potential in these regions. Since the amount of power can be implemented remains unknown in these studies, more technical constraints on PV power generation should be considered to produce a more comprehensive potential assessment.

To find generation potential, Okoyea et al. [15] used solar diffuse radiation models to predict the available solar potential for selected locations in nine sites located in eight states in Nigeria for inclined, single-axis and dual-axis tracking systems. Hong et al. [16] developed a GIS-based optimization model for investigating the optimal slope of the installed PV panel and corresponding annual electricity generation of PV system in the country of Korea. In the case of China, Wang et al. [17] conducted experiments on three kinds of PV systems for the purpose of analyzing the relationship between conversion efficiency and environmental parameters, then the results were combined with GIS analysis to evaluate PV generation potential at the national scale. These studies investigated PV performance under technical details in an effective manner. On the other hand, due to the lack of the consideration for PV geographical constraints, the size and distribution of solar power generation potential were also not found among these studies.

Nevertheless, a small quantity of studies have evaluated the geographical and generation potentials for PV power generation in particular countries or regions. Yushchenko et al. [18] used a constant value of PV land requirements to estimate the overall PV generation potential in rural areas of West Africa (Economic Community of West African States Region). Potential estimation was also performed by IRENA [19] for the same region under different geographical selection criteria. On a national level, Charabi et al. [20] used a GIS-based spatial multi-criteria evaluation approach to identify the areas highly suitable for PV installations in Oman. And Anwarzai et al. [21] used the same method to assess implementable solar energies in Afghanistan. Existing research mainly concentrated on the areas in the Middle East and Africa where solar resource is abundant, aiming at realizing a low-carbon transition or addressing the lack of access to electricity. For China, the largest developing country with urgent need for renewable energy generation to ease tense power supply and realize sustainable development, only a few studies had been conducted to assess the size and distribution of PV generation potential. Sun et al. [22] performed a comprehensive assessment on solar PV generation in Fujian province of China. In national level, He et al. [23] did an excellent research evaluating the generation potential in China at provincial resolution. However, all these studies mentioned-above used a constant value of land requirements for large-scale PV, despite the fact that the land occupied for large PV projects vary considerably under different geographical locations and technical factors [24]. Evidence of errors due to similar practices can be found in potential estimates for other renewable energy sources. For example, a recent study by Keith et al. [25] pointed out that global wind resource potentials have been widely overestimated because the area of land occupied in practice by installations has been higher than predicted. For solar power, the average power density (W/m^2) is 10 times higher than for wind power, but also much lower than estimates by leading energy experts [25]. Land use for large-scale PV has attracted extensive attention these years, which has been regarded as an important issue by China's government in the third national land survey [26]. However, there is still a lack of research on incorporating accurate land conversion factors into high-solution PV potential estimates for China. Additionally, a consensus on land selection criteria in terms of minimum GHI (Global Horizontal Irradiance) and maximum slope accepted for large-scale PV installations has not yet been reached (see Table 1). Furthermore, the environmental benefits associated with the solar power generation potential were not addressed in previous studies, which need further investigation.

On the whole, research on large-scale PV generation potential still exists unsolved issues over land selection criteria, land use requirements and associated environmental benefits, while only a few studies focused in China. The objective of this study is to conduct a comprehensive estimation of the large-scale PV potential in China with high resolution based on the best currently available solar radiation data,

Table 1
Summary of not-reached consensus on land requirements and land selection criteria for large-scale PV installations.

Criteria	Yushchenko et al. [18]	Charabi et al. [20]	He et al. [23]	IRENA study [19]	Anwarzai et al. [21]
Solar irradiance	Not evaluated as exclusion criteria[a]	Not evaluated as exclusion criteria[a]	Not evaluated as exclusion criteria[a]	Min. annual GHI 1000 kWh/m^2	Min. annual GHI 1278 kWh/m^2
Max. slope for PV plants	10% (or 5.7 degrees)	5 degrees	1–3% (or 0.6 degree-1.7 degrees)	20% (or 11.3 degrees)	5 degrees
Land use index for PV plants	Land occupancy factor of a 4[b]	Area factor of a 70%[c]	Land conversion factor of a 30 MW/km^2	Land occupancy factor of a 5[b]	Land occupancy factor of a 4[b]

[a] These three studies used the values of annual GHI to determine the land suitability for large-scale PV installation, but did not exclude the generation potential in regions with insufficient irradiance.
[b] According to these three studies, land occupancy factor represents the ratio of total land required to the surface of PV panels.
[c] The authors of this study used a term "area factor" and give the following definition: "The area factor, indicates what fraction of the calculated areas can be covered by solar panels.

geographic data, and land use conversion factors. The outcomes will provide basic information to aid policymakers and installers in optimizing deployment of large-scale PV plants across the country, and will give examples for other countries worldwide. To realize this goal, this study is conducted in the following five steps: (i) identifying the geographic potential for large-scale PV installations in China and its distribution within the software ArcGIS; (ii) using different land conversion factors for different PV systems and power plants locations to accurately estimate corresponding generation potential on both national and provincial level; (iii) calculating associated CO_2 emission reduction potential and its consequent impact on national carbon intensity reduction when substituting large-scale PV for current power sources under three different scenarios; (iv) investigating the influence of different geographical criteria and technical factors on total generation potential through sensitivity analysis; and (v) providing discussions on the implementation of large-scale PV generation potential under the constraints of China's power transmission network.

The novelties of this research are elaborated as follows. Firstly, this study fills the gap of the scientific knowledge on the size and distribution of solar PV power generation potential under geographical and technical constraints in China. Secondly, various land conversion factors for large-scale PV under different geographical and technical conditions, which are reliably calculated from the PV land use index issued by China's National Ministry of Land and Resources, are for the first time used for a high resolution technical potential estimation. Thirdly, this paper also calculates the associated CO_2 reduction potential from a life cycle perspective to validate the important role of large-scale PV in meeting China's emission reduction commitment and mitigating climate change, enabling policy makers to better relate the development of large-scale PV to low carbon strategies. Last but not least, a discussion considering gaps between generation capacity potential and current China's power transmission grids capacity is conducted, to provide valuable information for the future planning of the inter-regional transmission grid expansion.

2. Methodology

The framework for a large-scale PV potential assessment can be seen in Fig. 1. This study first uses two exclusion criteria to exclude areas of China unsuitable for the installation of large-scale PV plants. For the suitable areas identified, the geographical potential are determined using the solar radiation intensity. The assessment of generation potential mainly focuses on the use of land conversion factors for large-scale PV plants, which vary between different locations and technical factors. In order to accurately assess generation potential, an area statistics process is conducted for PV suitability land by different slope and latitude categories. The potential installed capacity can then be estimated using the results of area statistics process and land conversion factors obtained. Finally, solar radiation and system efficiency data are combined to calculate the generation potential, and a discussion of the results is presented. The entire land selection and area statistics processes are performed using ArcGIS software. (Version: 10.4.1)

2.1. Selection of land suitable for PV

This paper excludes protected areas and unsuitable land cover from the areas suitable for large-scale PV installations. Information on China's protected areas is given by the Chinese Academy of Sciences [27]. Since protected areas plays an important role in keeping the balance of nature, these areas are not suitable for the construction of large-scale PV power plants. GlobCover 2009 data, obtained from the European Space Agency (ESA) GlobCover Portal [28], is used to rule out areas of the unsuitable land types for PV installations. GlobCover 2009 data classifies land areas across the globe into 22 classes with a resolution of 300 m. Generally, land areas with values of 30 (mosaic vegetation), 140 (closed to open grassland), 150 (sparse vegetation) or

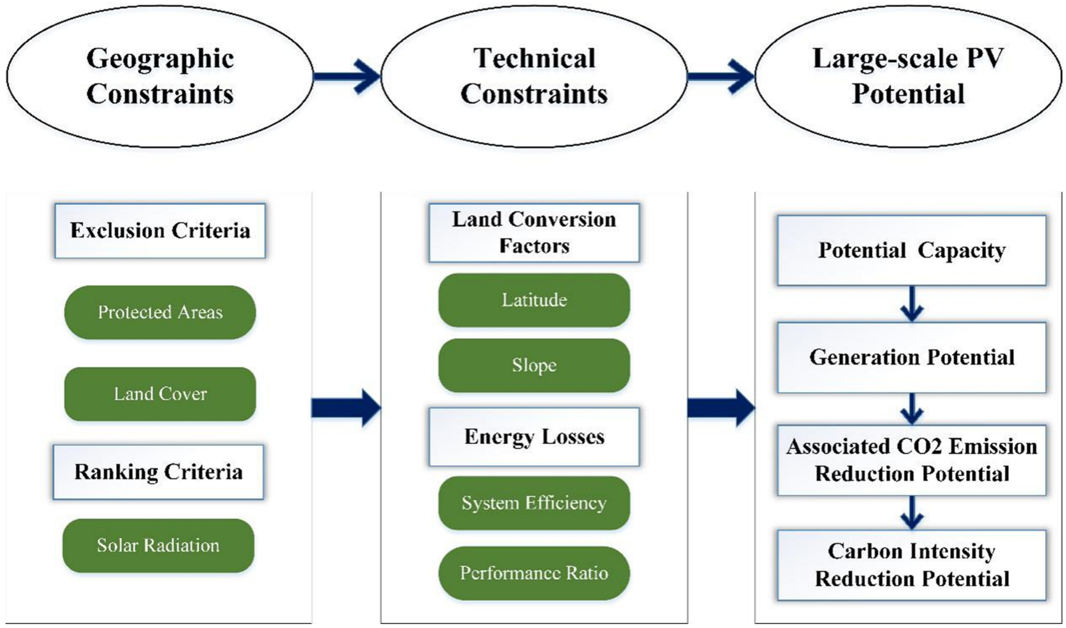

Fig. 1. The framework for assessing large-scale PV power generation potential in China.

200 (Bare areas) are regarded as suitable for large-scale PV installations [13]. The other 18 land types consist mainly of farmland, dense surface vegetation, water bodies and built-up areas. A PV suitability map is obtained by excluding the unsuitable areas. This study uses GHI as a ranking criterion because adequate solar radiation is essential for good PV power generation performance. Because GHI data from the NASA SSE satellite database is low-resolution and tends to give overestimates, this study uses solar radiation data from WorldClim [29], which gives the average monthly GHI measured during 1970–2000. WorldClim is a reliable data source that derived from the interpolated monthly values of weather station data, which could provide readily available information on ecosystem [30]. Using ArcGIS, the value for each month is multiplied by the length of the month and all of the values are added to give an estimate for the annual GHI. This paper then classifies areas suitable for PV into different categories depending on solar radiation levels to reflect the fact that suitable areas with higher annual GHI have more geographical potential.

Consistence with studies conducted by Yushchenko et al. [18], Charabi et al. [20], and He et al. [23], this research identifies annual GHI as a crucial factor for the level of resource abundance, but areas with poor GHI are not exclude from the total potential estimation. A few studies [11,19,21] set their boundary lines for minimum GHI allowed in studied region, with the reason that the corresponding generation in areas with poor solar irradiance is not cost competitive with conventional electricity sources. Since cost competitive for PV generation is dependent on various factors such as utilization hours, PV system costs, subsidies, and capital costs [2], the areas with relatively low GHI should not be excluded from regional potential assessment. As presented in Table 1, there is also a wide range of maximum accepted slope for plants installations set in previous studies from 0.6 to 11.3 degrees (or 1–20%). To fully evaluate the generation potential in different land selection criteria, we applied a different slope ranges to conduct the estimation. According to the land use index issued by China's National Ministry of Land and Resources [24], lands for PV installations can be classified using into different categories by slope ranges: (1) type I (slope less than 3 degrees); (2) type II (slope more than 3 degrees and less than 20 degrees); (3) type III (slope more than 20 degrees). Each type of land has different land conversion factors for PV installations. For our results can be better adapted to different situation in practice, a sensitivity analysis for generation potential under different land selection criteria on GHI and slope is provided in Section 3.4.

2.2. Land conversion factors

The geographical potential assessment gives us the areas suitable for large-scale PV plants. Land requirement for PV project installations is essential to calculations of the potential solar capacity in these areas. As shown in Fig. 2, it is necessary to leave spaces between PV arrays to prevent shadow effect [31]. The minimum distance needed can be calculated using following equation:

$$D = D1 + D2 = (L' \times \cos Z) + (L \times \sin Z) \times \cos\beta/\tan\alpha \qquad (1)$$

where β is the solar azimuth angle, α is the solar elevation angle, L′ is projection length of sunlight on the ground, H is the relative height between the front and rear PV arrays, L is the vertical width of the PV array and Z is the tilt angle of the PV array. Since the solar azimuth and elevation angles are closely related to latitude and the relative height between PV arrays is dependent on slope, the land conversion factors for large-scale PV plants are strongly dependent on latitude and slope. At low latitudes the sun is relatively high in the sky and so PV arrays cast shorter shadows, meaning that the land area needed for PV installations of a given capacity is smaller than that needed at higher latitudes. Since steep land makes construction, especially of large installations, difficult, and relatively flat areas are needed for large-scale PV power stations. The International Centre for Tropical Agriculture (CIAT) provides database on global land elevation information with a high resolution of 90 m [32]. This study uses ArcGIS software to extract the slope from the SRTM data (version 4).

While land use requirement for large-scale PV varies considerably under different geographical and technical conditions, existing studies on PV generation potential applied a constant value to calculate the generation potential. A more comprehensive land use index is needed for accurate estimation. In order to implement the land use control standards for PV projects, and further promote land conservation and utilization, China's National Ministry of Land and Resources issued the regulation titled *Land Use Control Index for PV Station Project* in 2016 [24]. The control index includes the land requirements for PV system deployment, substation and manage center as well as on-sites electro circuit and roads. The index is classified into three categories by slope, which has been stated in Section 2.1. The land control index also specifies the maximum areas occupied allowed for the whole power plants

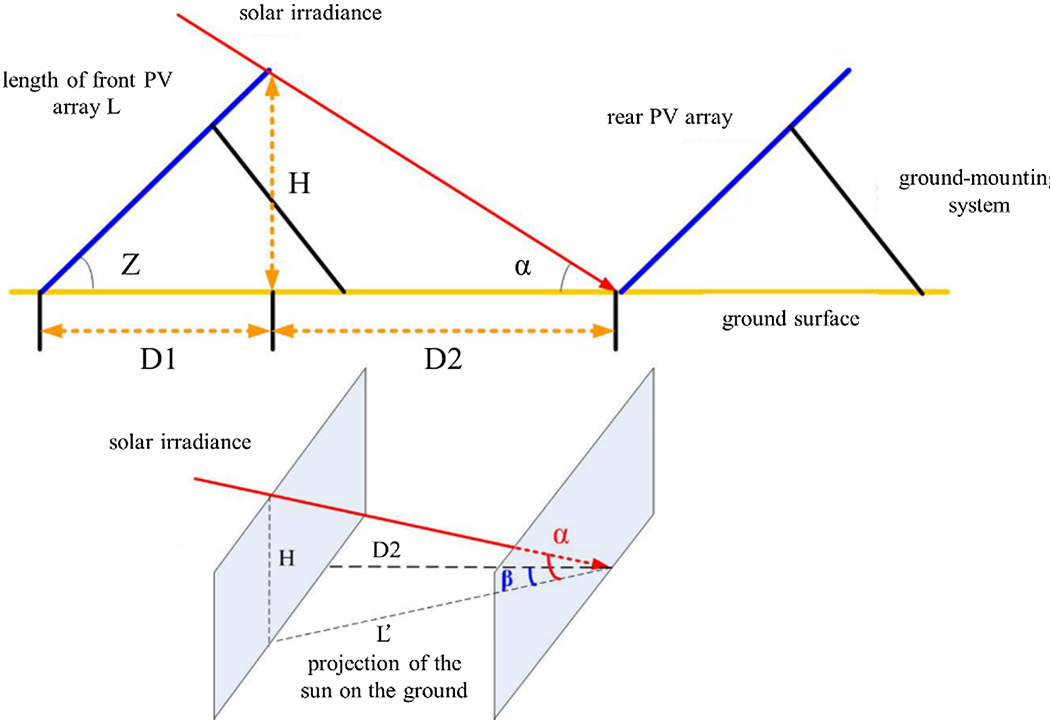

Fig. 2. Minimum distance needed between front and rear PV arrays to prevent shadow effect.

Table 2
Land conversion factors for large-scale PV with in China when PV system efficiency is 14% with fixed-mounted system (ha/per 10 MW installed capacity). The authors compile the data with information in [24]. Note the vacuum numbers are due to that there is no suitable land for large-scale PV installations in areas belonging to these categories.

Slope	Latitude								
	18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
< 3 degrees	14.36	14.93	15.60	16.26	17.18	18.09	19.22	20.56	21.90
3–20 degrees	18.14	18.92	19.78	20.65	21.84	23.04	24.50	26.24	27.97
> 20 degrees	/	/	23.98	25.04	26.51	27.98	29.78	31.92	34.05
	36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
< 3 degrees	23.97	26.06	28.94	32.61	36.28	44.34	52.41	60.47	68.539
3–20 degrees	30.68	33.39	37.13	41.91	46.68	57.16	67.65	78.13	88.613
> 20 degrees	37.39	40.73	45.33	51.20	57.08	69.98	82.88	/	/

under different latitudes, PV system efficiencies and ground-mounting methods, thus providing a valuable reference for land conversion factor for large-scale PV in China. The land conversion factor for large-scale PV under specific geographical and technical conditions can be calculated by interpolation based on the index. This study chose a conservative PV system efficiency of 14% and fix-mounted system as our baseline to calculate the generation potential. The land conversion factors under this situation is presented in Table 2. In order to estimate the generation potential accurately, the total areas of suitable land falling into the different categories are found. A sensitivity analysis for total generation potential under different technical factors including PV system efficiency between 11% and 20% and single/double-axis systems is also provided in Section 3.4, with their corresponding land conversion factors presented in Appendix A.

2.3. Evaluating the generation potential

The following equation is used to determine the output of PV panels (the PV Energy Potential or PVEP) across China:

$$\mathrm{PVEP(kWh)} = \sum_{l=18}^{50}\sum_{s=1}^{3}\frac{\mathrm{LA}}{\mathrm{LCF}}\times 10\ \ \mathrm{MW}\times \mathrm{GHI}\times \mathrm{GSR}\times \mathrm{PR}\times(1-\mathrm{SF}) \tag{2}$$

where l refers to different latitudes and s refers to three kinds of slope ranges across China. LA refers to available land area suitable for PV. LCF refers to land conversion factors. GSR refers to generator to system ratio. PR refers to performance ratio, and SF refers to shading factor. According to a study by Nuria [33], standard values in China for generator to system ratio is 0.8, a performance ratio of 0.8 and a shading factor of 0.05 are also used. This study uses land conversion factors with units of ha/10 MW. We therefore estimate the generation potential by dividing the available land area suitable for PV with a particular land conversion factor by that land conversion factor and then multiplying by 10 MW, the annual GHI and other constant factors, as seen in Eq. (2). The national and provincial power generating potentials for large-scale PV can then be found by summing over all of these land areas with particular conversion factors in the relevant region.

2.4. The associated carbon intensity reduction

China made a commitment on reducing its carbon intensity with a series of ambitious renewable energy development plans are being implemented. Therefore it is useful to investigate the reduction in CO_2 emissions which would result if the generation potential for large-scale PV were fully realized as a replacement for current methods of power generation in China.

Projected data for China's provincial electricity demand in 2030 is obtained from the Electricity Supply and Demand Laboratory of the State Grid Energy Research Institute [34], and a value of 0.0873 kg CO_2/kWh for the carbon footprint of large-scale PV in China from a previous Life Cycle Assessment (LCA) study is used [7]. Operating margin and build margin of China's power grids (kg CO_2/kWh) are used to calculate the CO_2 emission factors (kg CO_2/kWh) of China's six main power grids. The operating margin is the emission factor of the marginal emission associated with the operation process of a group of existing power plants whose current electricity generation would be affected [35]. The build margin is the emission factor of the marginal emission associated with the building process of a group of prospective power plants whose construction and future operation would be affected [35]. Combined margin is the result of a weighted average of operating margin and build margin. The combined margin method is widely used in the calculation of CO_2 emission factors for national power grids [36]. The only difference is that different studies adopted different methods to determine the weights between operating margin and build margin. This study applies the default weight of 0.5 for both operating margin and build margin, as first proposed by Lawrence Berkeley National Laboratory [36] and also suggested by Synapse Energy Economics, Inc. [37]. As ACM0002 method proposed CM can be obtained by a simple average of the OM and BM, the equation can be expressed as:

$$\text{Emission factor} = \text{Combine Margin} = 0.5 \times \text{Operating Margin} + 0.5 \times \text{Build Margin} \quad (3)$$

Data on the operating and build margin for the six main China's grids are obtained from the Institute for Global Environmental Strategies (IGES) [38]. The emission factors obtained are shown in Table 3. The operating and margin of Tibet, Hong Kong, Macao and Taiwan are unavailable, so these areas are excluded from further analysis.

For this estimation, we assume that the carbon footprint of large-scale PV and the emission factors of the Chinese power grids will remain constant in 2030 due to a lack of forecasts. There are three scenarios in this study for the estimation of carbon intensity reduction in China 2030. Scenario 1 is BAU (business as usual) scenario, and intervention measures are not taken under this scenario. We assume a 5% of annual growth for GDP and a 3% annual growth for national CO_2 emissions till 2030 under this scenario. Both scenario 2 and scenario 3 assume current power generation can be fully substituted by local large-scale PV generation in 2030. However, the gap between power demand and generation potential in areas with insufficient potential cannot be fixed by importing power from other provinces through inter-regional power transmission grids under scenario 2. So the generation potential for a particular province represents the maximum amount of PV-generated electricity that can be substituted for other energy sources for that province. So if the generation potential is larger than power demand, the equation for calculating CO_2 emission reduction can be expressed as following:

$$\text{Emission reduction} = (\text{Emission factor} - \text{PV carbon footprint}) \times \text{Power demand} \quad (4)$$

If the generation potential is smaller than power demand, the equation will be transformed as:

$$\text{Emission reduction} = (\text{Emission factor} - \text{PV carbon footprint}) \times \text{Generation potential} \quad (5)$$

While scenario 3 assumes large-scale PV power transmission between the grids could be fully realized in 2030. The emission reduction can be calculated by Eq. (4). The results combined with projected data for China 2030 investigate if those emission reduction potential is sufficient to meet China's carbon intensity reduction commitment.

Table 3
Emissions factors for Chinese power grids (kg CO_2/kWh).

Regional grid	Emission factor in years 2011–2013		
	Operating margin	Build margin	Combined margin
North China Grid	1.0416	0.4780	0.7598
Northeast China Grid	1.1291	0.4315	0.7803
East China Grid	0.8112	0.5945	0.7029
Central China Grid	0.9515	0.3500	0.6508
Northwest China Grid	0.9457	0.3162	0.6310
Southern China Grid	0.8959	0.3648	0.6304

3. Results and discussion

3.1. Geographical potential

Fig. 3(a) depicts the areas suitable for the installation of large-scale PV plants in China. There is 3.79871×10^{12} m^2 of suitable land, accounting for 39.43% of China's total land area. Most of the suitable land is found in northwestern China and Tibet, particularly in Xinjiang (32.39% of the total suitable land), Tibet (22.28%), Inner Mongolia (17.81%), Qinghai (9.20%) and Gansu (5.72%). It worth noting that the other provinces, which account for 46% of China's total land area, only contain 13% of the total suitable land area. This is because considerable portions of these provinces are covered by dense vegetation, and areas of dense vegetation are not suitable for large-scale PV plants because the vegetation would be damaged by their construction. Further research is needed to investigate the impacts on ecology of cutting down lush vegetation to build solar power plants.

Fig. 3(b) and (c) show the areas suitable for large-scale PV plants categorized by slope and GHI. Based on the results of the slope extraction in ArcGIS, type I, type II, and type III land constitute 71.03%, 28.45% and 0.52% respectively of the land suitable for large-scale PV plants in China. Flat land therefore dominates the land area suitable for large-scale PV. The areas with an annual GHI above 1500 kWh/m^2 are mainly concentrated in Hainan, western Inner Mongolia, northern Ningxia, north-western Gansu, Qinghai, and most areas of Xinjiang and Tibet. Tibet and Northwest China have especially high geographical potentials due to the sparse vegetation, gentle slopes and adequate solar radiation in these areas.

3.2. Generation potential

The estimation for potential solar capacity, based on available land area and the use of land conversion factors, show that the total installed capacity of large-scale PV in China could be up to 1.41×10^5 GW, or 1251.8 times the cumulative installed capacity of China in the first half of 2018. The power generation at maximum installed capacity would be 1.38874×10^{14} kWh, or 21.4 times the total national electricity production of China in 2016. These results show that there is significant scope for the further development of large-scale PV in China. The generation potential from PV is more than sufficient to meet China's national power needs. To investigate the distribution of the potential in greater detail, estimation have also been made at the provincial level. The results can be seen in Figs. 4 and 5.

Fig. 4 shows the variation in the potential for large-scale PV development between 31 provinces in China. Tibet, with abundant solar

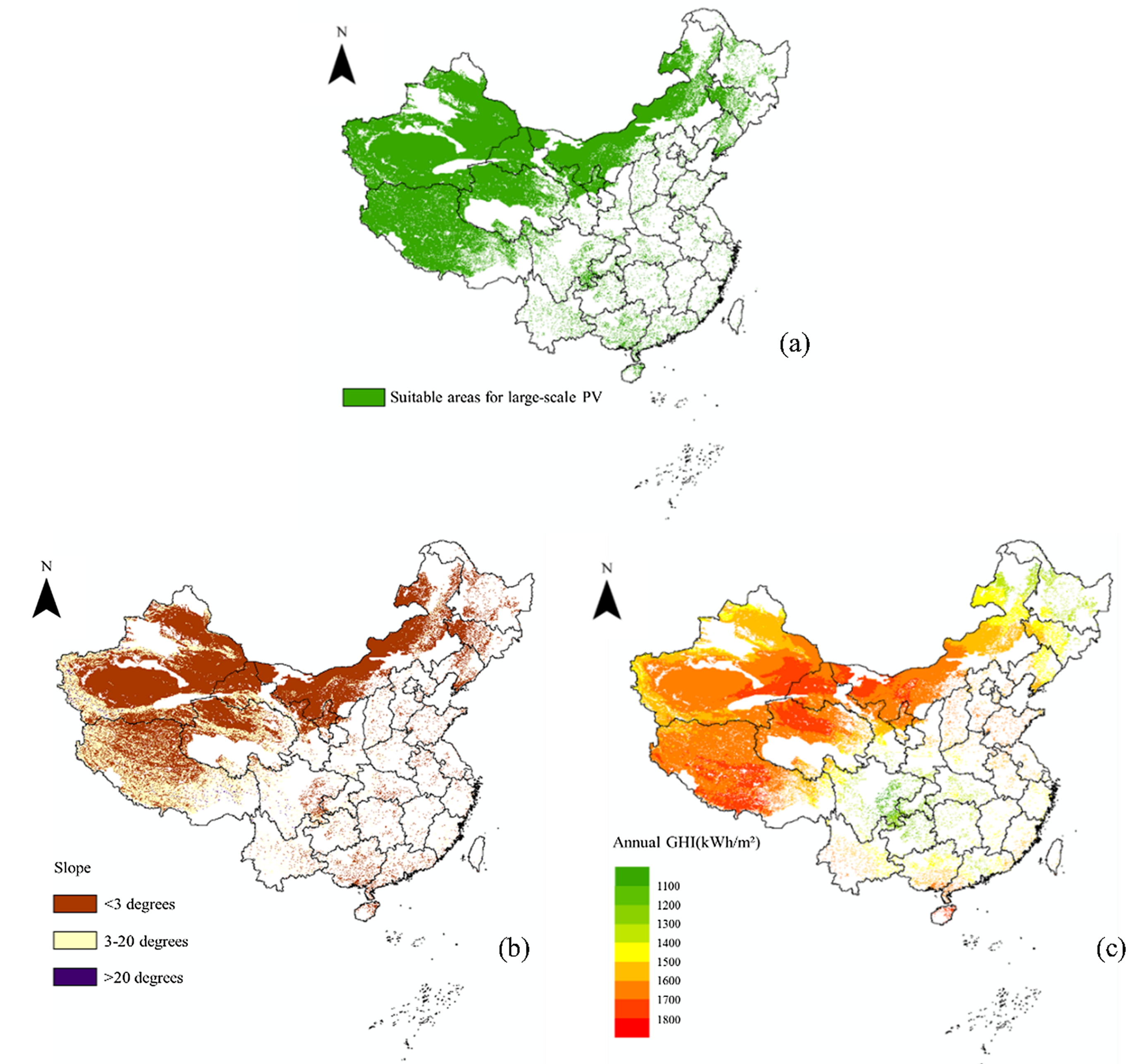

Fig. 3. Results of the land selection process in ArcGIS. (a) Areas of China suitable for large-scale PV plants, (b) Areas suitable for large-scale PV plants categorized by slope: type I (< 3 degrees), type II (3–20 degrees) and type III (> 20 degrees), (c) Areas suitable for large-scale PV plants categorized by annual GHI.

radiation and at present a low installed capacity, has the greatest potential for further expansion of large-scale PV. The northwestern provinces of Xinjiang, Qinghai, Inner Mongolia, and Gansu are at the forefront of current large-scale PV deployment and still show significant potential for further development due to the high geographical potential in these areas. By contrast, provinces like Jiangsu, Ningxia, Hebei, Henan, Shandong, Shanxi and Anhui also have a high degree of current PV development, but the potential for further expansion is relatively low. Guangxi, Sichuan, Chongqing, Jilin and Heilongjiang also have a high potential for future development, but the GHI in these areas is relatively low, which may be a barrier to actual deployment.

Fig. 5 shows the potential for large-scale PV generation to match local electricity consumption in 31 of the provinces of China. To produce this, data on provincial electricity consumption in 2016 from China's National Bureau of Statistics [39] was used. The results show a strong imbalance between potential for large-scale PV development and economic development. The provinces with the greatest generation potentials are Xinjiang, Tibet, Inner Mongolia, and Qinghai, which together account for 82% of the national potential for large-scale PV. Their total potential is a remarkable 202 times their electricity consumption in 2016. However, China's economically developed coastal provinces, which contributed 49% of China's GDP and accounted for 32% of China's population in 2017, only account for 1% of the national large-scale PV generation potential, which is equivalent to 0.71 times their power consumption in 2016. Local large-scale PV development will therefore be insufficient to meet the power needs of these areas. The ratio of local generation potential to electricity consumption for Shanghai, Beijing and Tianjin in particular are rather low due to the scarcity of available land in these areas and their huge power consumption. Therefore, the real challenge facing large-scale PV

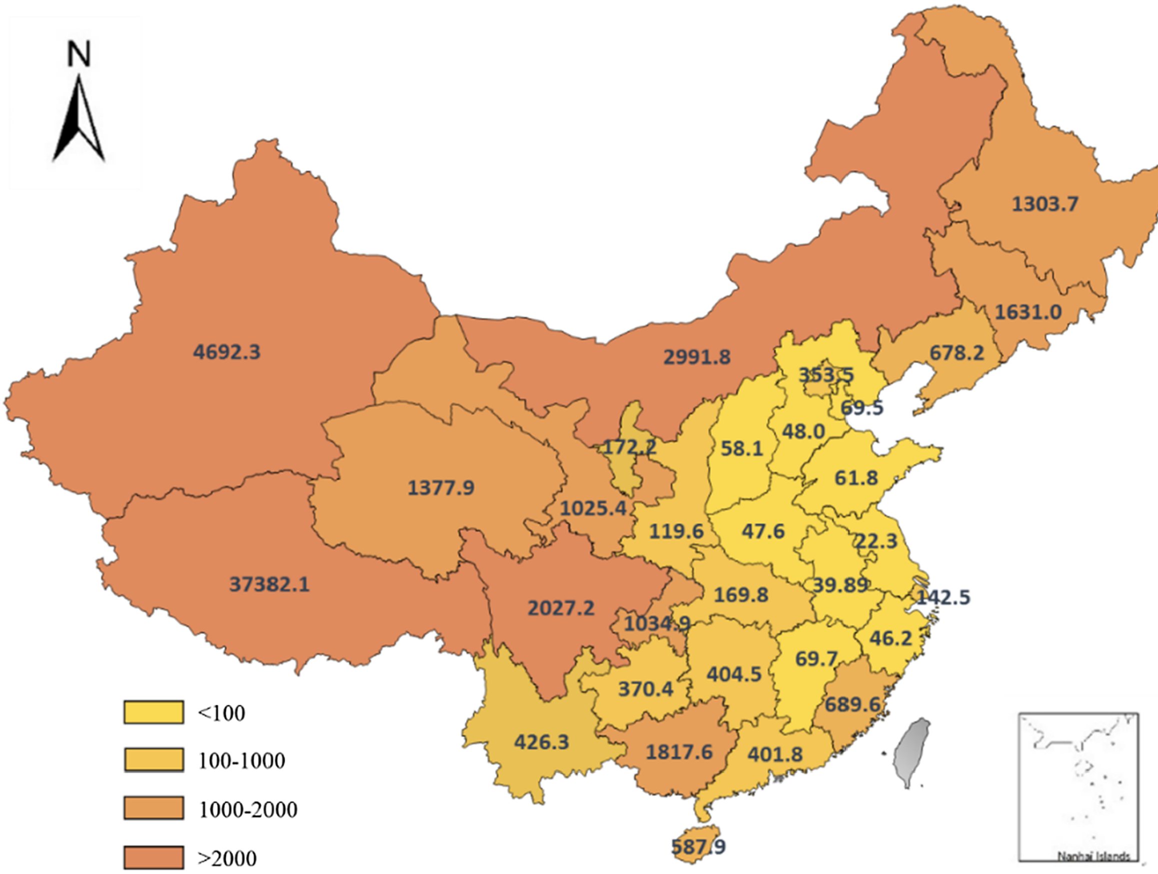

Fig. 4. Ratio of large-scale PV generation capacity potential to recent cumulative installed large-scale PV capacity at provincial resolution in China.

development in China is the power transmission between different provinces and regions. A discussion on how to utilize these generation potential in the real future exploitation is provided in Section 3.5.

3.3. Associated CO_2 emission reduction

Based on the generation potential we obtained in Section 3.2, we calculate the associated CO_2 emission reduction potential and the results are presented in Fig. 6.

All regions of China except those in the North China and Jiangsu, Zhejiang as well as Fujian, have sufficient generation potential to meet their power demand by vigorously developing large-scale PV generation as a substitute for current power generation. National potential CO_2 emission reductions would reach 4301 Mt of CO_2 in 2030 under scenario 2. While Xinjiang and Qinghai possess a high PV resources availability, they are not promised to bring significant CO_2 reduction due to the low power demand. Emission reduction potential would be massive when provinces embrace both high generation potential and electricity consumption such as Inner Mongolia, Guangdong and Liaoning. The huge gap between power demand and PV resources would still exist in Beijing, Tianjin, Shanghai, Jiangsu and Zhejiang in 2030, with insufficient emission reduction benefits. If inter-regional transmission of large-scale PV power could be fully realized (scenario 3), an extra 1670 Mt of CO_2 emissions would be prevented in 2030. From an international perspective, a new IPCC report [40] pointed out the global CO_2 emission are headed to 56,000 Mt in 2030 but should be controlled below 27,500 Mt to consistent with temperature control target. Thus associated CO_2 emission reduction potential for large-scale PV in China would contribute a percentage of 15% (scenario 2) to 21% (scenario 3) to achieve this goal.

Based on the associated CO_2 emission reduction potential we obtain above, we calculate the corresponding carbon intensity reduction under three scenarios. The result is presented in Table 4. Xu et al. [41] forecasted that China's GDP will reach 105,200 billion Yuan (at the 2005 price) in 2030. According to data provided in a climate change report by the Chinese government [42], China's national CO_2 emissions were 5975 Mt in 2005, corresponding to a carbon intensity of 3.19 t/10^4 Yuan. Given the fact that at the Paris Convention, China committed to achieving a reduction in carbon intensity by 2030 of at least 60% as compared to 2005, national CO_2 emissions in 2030 should be controlled below 13,425 Mt. Liu et al. [43], however, forecasted that China's CO_2 emissions will increase by 3% per year until 2030 if more intervention measures are not taken (scenario 1). Based on China's CO_2 emissions in 2012 from government report [44], this would lead to CO_2 emissions of 16,842 Mt CO_2 in 2030, representing a reduction in national carbon intensity of less than 50% as compared to 2005. If we manage to totally replace fossil fuel-based power generation with large-scale PV power generation by 2030 (scenario 2), CO_2 emissions in 2030 will be reduced to 12,541 Mt, corresponding to a reduction of national carbon intensity to 1.19 t/10^4 Yuan, which would be a reduction of 63% as compared to 2005. This percentage would increase to 68% if the transmission of significant amounts of power between provinces can be fully realized (scenario 3). We use the same method to estimate the national carbon intensity based on data provided by CEADs [45] and find that the associated national carbon intensity reduction is 70% under scenario 2 and 75% under scenario 3. In general, these results show that development of large-scale PV can greatly contribute to the fulfilment of China's emission reduction commitment and mitigation on the global climate change.

3.4. Sensitivity analysis and uncertainties

In order to investigate the influence of different land selection criteria and technical factors on large-scale PV generation potential at the

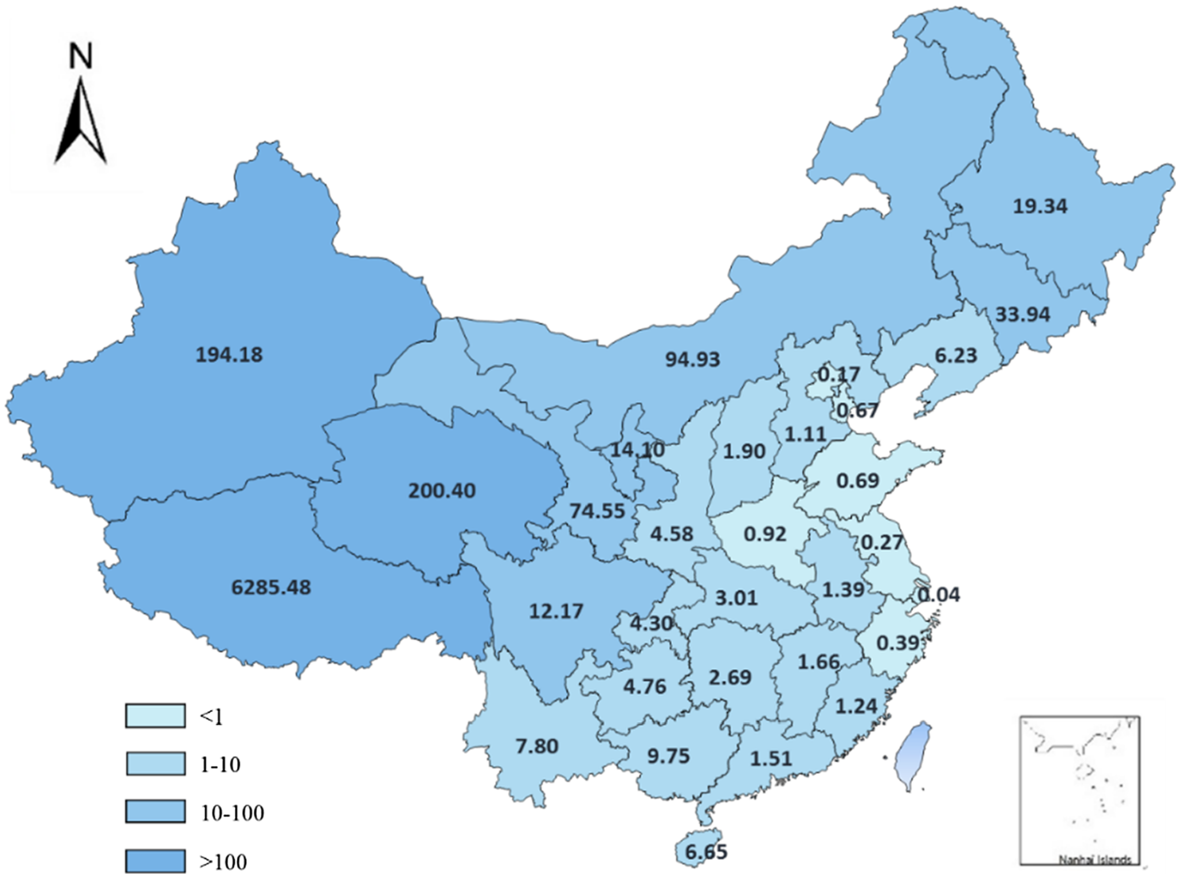

Fig. 5. Ratio of provincial large-scale PV generation potential to provincial electricity consumption in 2016.

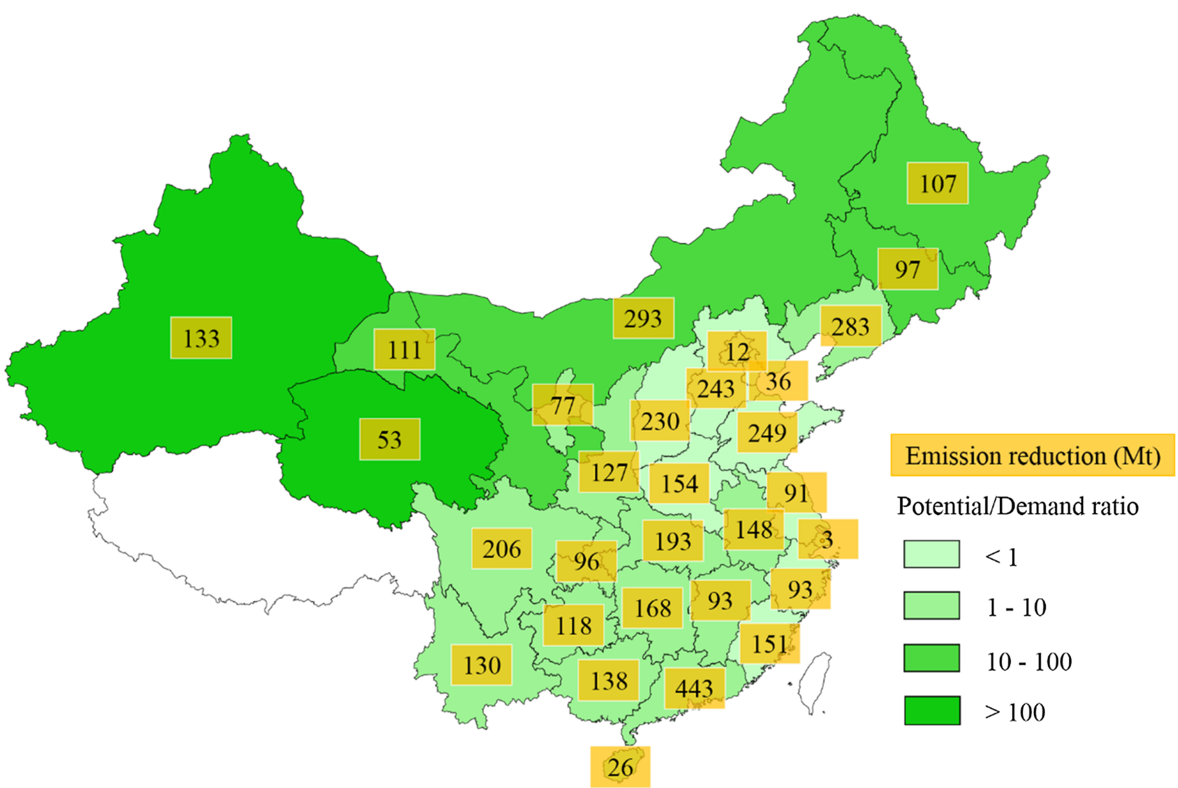

Fig. 6. Ratio of large-scale PV generation potential to power demand in 2030 at provincial resolution, with associated CO_2 emission reduction potential.

Table 4
Associated carbon intensity reduction potential in China 2030.

Scenario	CO_2 emission (t)	GDP (10,000 Yuan)	Carbon intensity (t/ 10,000 Yuan)	Carbon intensity reduction
2005 Baseline	5.98×10^9	1.87×10^9	3.19	/
1	1.68×10^{10}	1.05×10^{10}	1.60	−49.82%
2	1.25×10^{10}	1.05×10^{10}	1.19	−62.63%
3	1.09×10^{10}	1.05×10^{10}	1.03	−67.61%

national level, and to make results in this paper better applicable to future energy policies, a sensitivity analysis is provided in this section.

To make the results of generation potential could be better applied to future land selection for large-scale PV projects in practice, this paper applies different values of GHI and slope ranges as exclusion criteria to calculate corresponding national generation potential. Since an annual GHI higher than 1400 kWh/m^2 and slope lower than 3 degrees has been widely used in previous studies as a threshold for PV installation to be feasible, here we conduct sensitivity analysis on these two key assumptions, and the result can be seen in Fig. 7. The results show that the generation potential will not change substantially when minimum annual GHI allowed is set between 1000 kWh/m^2 and 1400 kWh/m^2, while the overall potential is most sensitive to the 1600 kWh/m^2 annual GHI threshold. Nearly 55% of generation potential comes from the areas with slope less than 3 degrees and annual global horizontal irradiance over 1600 kWh/m^2, accounting for an approximate 49% of suitable lands for large-scale PV installations or 19% of China's total land areas. Therefore these areas should be identified as hot spots for large-scale PV installations to obtain best power generation benefits with minimum installations costs. On the other hand, the generation potential values almost remains unchanged between no matter when the slope threshold is set at 20 degrees or no limit. This result indicates the generation potential in areas with slopes greater than 20 degrees is rather low. In addition, the installations in these areas would be difficult and costly, with a higher land use required. Thus the development of large-scale PV in areas with slope higher than 20 degrees should not be encouraged.

The influence of different PV system efficiencies and ground-mounting methods on large-scale PV generation potential is presented in Table 5. For each 1% increase in the efficiency of PV system within the range of 10–20%, the overall potential would increase 6.76×10^{12} to 1.04×10^{13} kWh, which represents 1.04–1.59 times of China's national electricity consumption in 2016. The generation potential for single-axis system with PV system efficiency of 18% is slightly lower than the fixed-mounted under the same efficiency. And the potential for double-axis system with efficiency of 22% is also lower than the potential for fixed-mounted system with a 19% efficiency. This is because single-axis and double axis mounted systems would occupy more space than fix-mounted systems due to the area required for tracking system installations [46]. Overall, these results indicate further improving of conversion efficiency and saving land use would contribute to a substantial increase in large-scale PV generation potential.

Table 5
The results of the sensitivity analysis of generation potential under different PV system efficiencies and ground-mounting methods.

Ground-mounting method	PV system efficiency	Generation potential (10^{14} kWh)	Change (%)
Fix	11%	1.09	−21
Fix	12%	1.2	−14
Fix	13%	1.28	−8
Fix	14%	1.39	0
Fix	15%	1.47	+6
Fix	16%	1.57	+13
Fix	17%	1.65	+19
Single-axis	18%	1.44	+4
Fix	18%	1.75	+26
Fix	19%	1.86	+34
Fix	20%	1.92	+38
Double-axis	22%	1.85	+33

Generation potential in our study is 98% higher than previous study conducted by He et al. [23]. The difference is mainly caused by different land selection criteria on slope. If we exclude the generation potential in areas with slope higher than 3 degrees, the difference will be reduced to 44%. The main novelties of this study is the application of different PV land conversion factors for different geographical and technical conditions. Thus the generation potential can be more accurately estimated. In addition, while He et al. [23] set a more strict exclusion criteria on slope of 3% (or 1.7 degrees), which would cause the ignorance of generation potential in technical feasible areas for large-scale PV installations. This study divides slope into three categories and then separately calculated the potential within each slope range, to make the generation potential results can be applied to different land selection criteria. To give an overview in real practice, a sensitively analysis for generation potential under different PV system efficiencies is conducted. Thus this study can be better applied to future energy policies.

The following section discusses the limitations of this study and potential avenues for further research. Li et al. [47] found severe air pollution in China has significantly reduced surface solar radiation

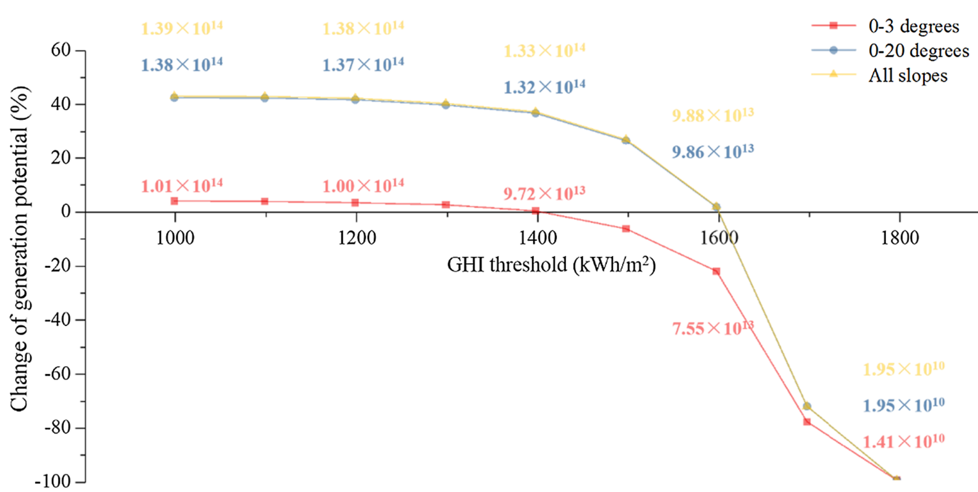

Fig. 7. The results of the sensitivity analysis of different land selection criteria involved in the potential generation estimation, and colored numbers indicate the potential within different slope ranges (in kWh).

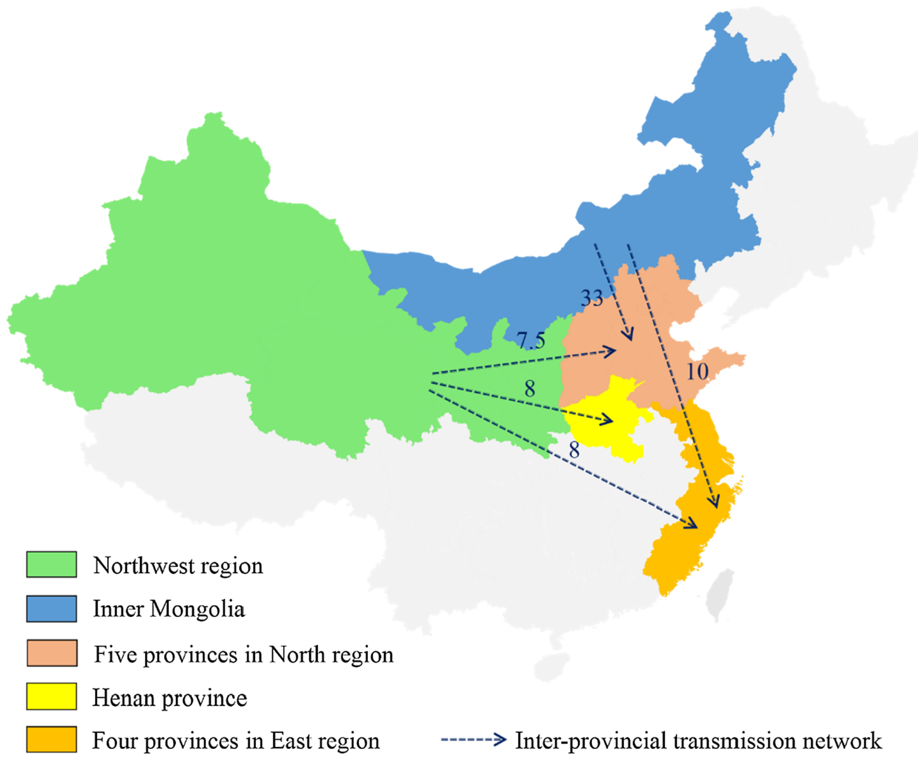

Fig. 8. The main inter-regional transmission grids from Northwest region and Inner Mongolia to other regions in 2017. Note that the numbers close to the lines indicate transmission capacity (in GW), and the arrows reflect the main directions of transmission flows. The authors compile the data with information in [55].

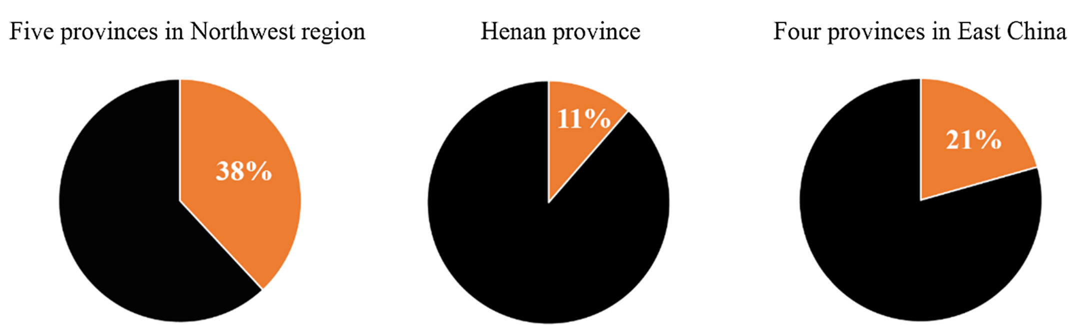

Fig. 9. The percentage of current inter-regional transmission capacity to that of a maximum large-scale PV scenario in the ten provinces with insufficient generation potential.

suitable for PV generation. Bergin et al. [48] found that air pollution in the form of dust and particulates can adhere to the surfaces of PV panels, which can also cause sizable reductions in solar energy production. However, the impact of ambient and deposited particulate matter on PV electricity generation was not considered in our estimate of potential, so this matter could benefit from further investigation. While generation of electricity using PV is regarded as a water-saving technology [49], PV panels must be washed frequently to generate as much electricity as predicted due to the adherence of particulates and dust to their surfaces [50]. This paper found there to be a high generation potential for large-scale PV in Northwest China, an area facing a severe water shortage. Further investigation of the constraints placed on the development of large-scale PV by water resources is therefore necessary. The constraints imposed on the development of large-scale PV by transportation networks also require consideration. However, since China has a well-developed road network, availability of transport options is not considered to be a constraint on PV development in this study. Despite the existence of these limitations, the potential for further technological progress should not be ignored. With the continued development of photovoltaic technology and further reduction of costs, large-scale PV will play an increasingly important role in China's power generation in the future.

3.5. Discussion on the implementation of large-scale PV generation potential

The results of our study shows generation potential for large-scale PV can meet China's national power demand in 2016 and 2030 by 21.4 times and 10.9 times. However, the uneven distribution of generation potential would pose a great challenge for future practical application. While the implementation of a 100% renewable power system requires a substantial increase for the capacity of inter-regional transmission grid [51], China has historically focused on development in the generation side with relatively limited investments in the grid. The total capacity of the inter-regional transmission was 80.95 GW by 2016, which was only 5.03% of national generation capacity [52]. Therefore, the development of inter-provincial transmission grids would be the main constraint to achieve a maximum large-scale PV scenario in China.

According to the results of as indicated in Section 3.2, generation potential in Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Jiangsu, Shanghai, Zhejiang and Fujian will not meet their power demand in 2030. The gap between power demand and generation potential together of these ten provinces in 2030 will add up to a 2.65×10^{12} kWh, accounting for 16% of national power demand. Among these ten provinces, five belong to Northwest region, four belong to East, and Henan belong to Central region, with the gaps of 4.37×10^{11} kWh, 1.58×10^{12} kWh and 7.01×10^{10} kWh, respectively. To realize a maximum large-scale PV scenario in China 2030, the gap between power demand and generation potential of these ten provinces should be fixed by importing large-scale PV power from other provinces. Since Northwest region and Inner Mongolia embrace a high generation potential with several UHV (Ultra High Voltage) inter-regional transmission grids in operation or planning, these regions should be a priority for providing inter-regional power to ten provinces with low generation potential. Fig. 8 presents the current network of inter-regional transmission grids from Northwest region and Inner Mongolia to these ten provinces. The total capacity of these inter-regional transmission girds is 66.5 GW, and corresponding annual transmission power is an approximate 5.82×10^{11} kWh or 22% of the total gap between generation and power demand of these provinces in 2030. It means that the capacity of inter-regional transmission grids from Northwest region and Inner Mongolia to these ten provinces should reach an approximate 300 GW to realize maximum large-scale PV scenario. While the long-term planning of the China's State Grid in 2030 has not yet been available, Li et al. [53] predicted the capacity of inter-regional power grid in these regions would reach 237 GW in China 2030, making the maximum large-scale PV scenario possible to achieve. The calculation outcomes also shows on a regional level (see Fig. 9) that the capacity of inter-regional transmission grids in North region, Henan province and East region in 2030 should be at least 2.6, 8.8 and 4.9 times that of in 2017, respectively. Since this study quantifies the uneven distribution of generation potential at the provincial level, the results could be used in optimizing large-scale power generation and transmission for better power system.

While the further expansion on power grid networks and infrastructure is essential for the future implication of large-scale PV power, Li et al. [53] pointed out that grid expansion in China is at risks of facilitating more use of low-efficiency coal generation across regions and result in more CO_2 emissions. To better promote these renewable generation potential to on-grid power, the planning of the transmission grid development should be coordinated with China's large-scale PV project deployment. For a better power grid development, an effective management mechanism with full knowledge of the size and distribution of China's renewable resource and technology level is needed [54]. Our study can provide decision-makers with the most updated information on large-scale PV power generation map of China, which would contribute to the future planning of the inter-regional transmission grid development.

4. Conclusions

This study uses 600 land conversion factors to carefully estimate the generation potential for large-scale PV power generation in China under various geographical and technical constraints. The associated CO_2 emission reduction potential is calculated and its impact on reducing national carbon intensity as well as mitigating climate change in different scenarios is also quantified. For our results could be better adapted to different situation in practice, generation potential under different geographical selection criteria and technical details is assessed through sensitivity analysis. A discussion on how to better promote these generation potential to on-grid power is also conducted.

The results show that there is great potential for further development of large-scale PV in China. 39.43% of China's land is suitable for large-scale PV installations, with the greatest proportions of such land found in Xinjiang (32.39%), Tibet (22.28%), Inner Mongolia (17.81%), Qinghai (9.20%) and Gansu (5.72%). According to the result obtained in Section 3.2, the current installed PV capacity represents less than 0.1% of the total large-scale PV potential of China. The potential power generation is estimated to be 1.38874×10^{14} kWh, which is 21.4 times China's national power consumption in 2016 and 13.4 times the projected national power demand in 2030. Nearly 49% of lands suitable for large-scale PV installations has a slope less than 3 degrees and annual global horizontal irradiance over 1600 kWh/m^2, accounting for 55% of national generation potential. These areas should be identified as hot spots for future deployment of large-scale PV project to obtain best power generation benefits with minimum installations costs. Further improvement on PV system efficiency would also contribute to the generation potential. For every 1% increase in the efficiency of PV system within the range of 10–20%, the overall potential would increase 6.76×10^{12} to 1.04×10^{13} kWh, which represents 1.04–1.59 times of China's national electricity consumption in 2016. If current fossil fuel-based power generation can be fully substituted by large-scale PV power generation in China 2030, an annual CO_2 emission reduction of a 4301–5971 Mt will be brought about. This would lead to a reduction in national carbon intensity (adjusted for gross domestic product) of an approximately 63–68% as compared to 2005, which would be sufficient to meet China's carbon intensity reduction commitment. What's more, this associated CO_2 emission reduction potential is also promised to help global CO_2 emission reduce to the level that consistent with 1.5 °C scenario in 2030 by a percentage from 15% to 21%.

On a provincial level, Northwest region and Inner Mongolia together account for 86% of total generation potential, while there are ten provinces belonging to North region, Central region and East region, cannot meet their power demand by implementing large-scale PV generation in 2030. To address the uneven distribution of generation potential and realize a maximum large-scale PV scenario in China 2030, the capacity of inter-regional transmission grids from Northwest region and Inner Mongolia to these ten provinces needs reach an approximate 300 GW. This study identifies the size and distribution of generation potential of large-scale PV in China, which would aid decision-makers to select most suitable areas for large-scale PV installations, and provide references for future policy in terms of CO_2 emission reduction and further expansion planning on inter-regional power transmission grids.

Acknowledgements

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Appendix A

See Table A1.

Table A1
Land conversion factors for large-scale PV in China under different PV system efficiencies for different technologies (in ha/per 10 MW installed capacity). The authors compile the data with information in [24]. Note the vacuum numbers are due to that there is no suitable land for large-scale PV installations in areas belonging to these categories.

Ground-mounting system	PV system efficiency	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
Fix-mounted system	11%	< 3 degrees	17.93	18.70	19.55	20.40	21.58	22.76	24.46	26.09	27.91
		3–20 degrees	22.82	23.82	24.93	26.04	27.57	29.11	30.99	33.21	35.43
		> 20 degrees	/	/	30.31	31.68	33.56	35.45	37.76	40.50	43.24
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	30.47	33.04	36.68	41.39	46.10	56.45	66.80	82.32	97.85
		3–20 degrees	38.91	42.40	47.20	53.32	59.44	72.90	86.35	99.81	113.26
		> 20 degrees	47.52	51.81	57.71	65.25	72.79	81.07	105.91	/	/
	12%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	16.44	17.14	17.92	18.70	19.77	20.84	22.15	23.71	25.27
		3–20 degrees	20.89	21.80	22.81	23.82	25.21	26.61	28.32	30.34	32.36
		> 20 degrees	/	/	27.70	28.94	30.66	32.37	34.48	36.97	
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	27.70	30.13	33.49	37.77	42.06	51.47	60.87	74.99	89.10
		3–20 degrees	35.52	38.69	43.05	48.62	54.19	66.42	78.65	97.00	115.35
		> 20 degrees	39.46	43.35	47.24	52.62	66.32	81.37	96.40	/	/
	13%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	15.38	16.03	16.75	17.48	18.47	19.46	20.68	22.13	23.58
		3–20 degrees	19.51	20.36	21.30	22.23	23.53	24.82	26.41	28.29	30.17
		> 20 degrees	/	/	25.84	26.99	28.58	30.18	32.13	34.42	36.76
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	25.84	28.10	31.21	35.19	39.17	47.90	56.64	67.73	78.82
		3–20 degrees	33.10	36.04	40.09	45.26	50.43	61.79	73.15	87.56	105.57
		> 20 degrees	40.37	43.98	48.97	55.34	61.70	75.68	89.66	/	/
	14%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	14.36	14.93	15.60	16.26	17.18	18.09	19.22	20.56	21.90
		3–20 degrees	18.14	18.92	19.78	20.65	21.84	23.04	24.50	26.24	27.97
		> 20 degrees	/	/	23.98	25.04	26.51	27.98	29.78	31.92	34.05
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	23.97	26.06	28.94	32.61	36.28	44.34	52.41	60.47	68.539
		3–20 degrees	30.68	33.39	37.13	41.91	46.68	57.16	67.65	78.13	88.613
		> 20 degrees	37.39	40.73	45.33	51.20	57.08	69.98	82.88	/	/
	15%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	13.53	14.09	14.72	15.34	16.20	17.06	18.12	19.37	20.62
		3–20 degrees	17.10	17.83	18.64	19.46	20.58	21.70	23.07	24.70	26.32
		> 20 degrees	/	/	22.58	23.58	24.95	26.33	28.02	30.02	32.02
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54

(continued on next page)

Table A1 (*continued*)

Ground-mounting system	PV system efficiency	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	22.58	24.53	27.23	30.67	34.11	41.67	49.23	58.56	67.88
		3–20 degrees	28.86	31.40	34.91	39.39	43.86	53.69	63.52	75.64	91.35
		> 20 degrees	35.15	38.28	42.60	48.10	53.61	65.71	77.80	/	/
	16%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	12.74	13.26	13.84	14.43	15.23	16.03	17.02	18.19	19.36
		3–20 degrees	16.07	16.78	17.51	18.27	19.31	20.36	21.64	23.16	24.68
		> 20 degrees	/	/	21.18	22.11	23.40	24.68	26.26	28.13	30.00
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	21.18	23.00	25.52	28.73	31.95	39.00	46.06	56.64	67.23
		3–20 degrees	27.05	29.42	32.69	36.87	41.05	50.22	59.39	73.15	86.91
		> 20 degrees	32.92	35.83	39.87	45.01	50.15	61.44	72.73	/	/
	17%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	12.42	12.62	13.17	13.71	14.47	15.23	16.16	17.27	18.36
		3–20 degrees	15.27	15.92	16.63	17.34	18.33	19.31	20.53	21.96	23.40
		> 20 degrees	/	/	20.09	20.97	22.19	23.40	24.89	26.66	28.42
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	20.09	21.82	24.19	27.23	30.26	36.93	43.59	53.58	63.58
		3–20 degrees	25.64	27.88	30.97	34.91	38.86	47.51	56.18	69.18	82.17
		> 20 degrees	31.18	33.94	37.74	42.60	47.45	57.51	67.58	/	/
	18%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	11.71	11.97	12.49	13.00	13.72	14.43	15.31	16.35	17.38
		3–20 degrees	14.47	15.07	15.75	16.42	17.35	18.28	19.42	20.76	22.11
		> 20 degrees	/	/	19.01	19.83	20.98	22.12	23.52	25.18	26.84
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	19.01	20.63	22.87	25.72	28.58	34.85	41.12	50.53	59.93
		3–20 degrees	24.22	26.33	29.24	32.95	26.67	44.82	52.97	65.20	77.44
		> 20 degrees	29.44	32.03	35.62	40.19	44.75	53.59	62.43	/	/
	19%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	11.31	11.45	11.94	12.43	13.11	13.79	14.62	15.61	16.60
		3–20 degrees	13.18	13.73	14.33	14.94	15.77	16.61	17.64	18.85	20.06
		> 20 degrees	/	/	18.14	18.92	20.01	21.10	22.43	24.01	25.58
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	18.14	19.67	21.80	24.52	27.23	33.19	39.15	48.08	57.02
		3–20 degrees	21.96	23.86	26.48	29.82	33.16	40.50	47.84	62.02	73.64
		> 20 degrees	28.05	30.51	33.92	38.26	42.60	51.53	60.46	/	/
	20%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	10.51	10.93	11.40	11.86	12.51	13.15	13.94	14.87	15.80
		3–20 degrees	13.18	13.73	14.33	14.94	15.77	16.61	17.64	18.85	20.06
		> 20 degrees	/	/	17.27	18.01	19.04	20.07	21.33	22.83	24.32
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	17.27	18.73	20.74	23.31	25.88	31.53	37.17	45.64	54.11
		3–20 degrees	21.96	23.86	26.48	29.82	33.16	40.50	47.84	58.84	69.85
		> 20 degrees	26.66	28.99	32.22	36.33	40.44	49.47	58.50	/	/

(*continued on next page*)

Table A1 (*continued*)

Ground-mounting system	PV system efficiency	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
Single-axis system	18%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	16.80	17.76	18.86	19.95	21.56	23.17	24.60	27.44	30.28
		3–20 degrees	21.34	22.60	24.03	25.45	27.55	29.64	32.33	35.61	38.88
		> 20 degrees	/	/	29.20	30.95	33.53	36.11	38.38	42.93	47.48
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	35.59	39.89	43.55	52.87	62.19	78.77	95.33	120.19	145.04
		3–20 degrees	44.48	50.08	58.37	69.36	90.34	101.89	123.44	155.77	188.09
		> 20 degrees	54.37	61.27	71.48	85.01	98.54	125.05	151.56	/	/
Double-axis system	22%	Slope	Latitude								
			18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36
		< 3 degrees	14.32	16.01	16.99	17.96	19.40	20.84	22.69	24.93	27.18
		3–20 degrees	19.20	20.33	21.60	22.87	24.74	26.61	29.01	31.93	34.85
		> 20 degrees	/	/	26.21	27.78	30.08	32.38	35.33	38.92	42.52
		Slope	Latitude								
			36–38	38–40	40–42	42–44	44–46	46–48	48–50	50–52	52–54
		< 3 degrees	31.02	34.87	40.56	48.10	55.65	74.62	93.60	122.06	150.52
		3–20 degrees	39.85	44.84	52.24	62.05	71.85	95.52	121.19	158.19	195.20
		> 20 degrees	48.67	54.82	63.92	75.99	88.06	118.42	148.78	/	/

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