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Quantifying the photovoltaic potential of highways in China

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HIGHLIGHTS

- A spatiotemporal model to estimate the photovoltaic (PV) potential of highways is developed.
- The dynamic shadows of the surrounding terrain on the highway surface are considered.
- By 2020, the mileage of Chinese highway was 143,684 km and the area was 3,957 km^2.
- The installed capacity and power generation of PV highways in China are 700.85 GW and 629.06 TWh, respectively.

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ABSTRACT

Installing photovoltaic (PV) modules on highways is considered a promising way to support carbon neutrality in China. However, collecting the area of the highway, and precisely assessing the shadow area of the highway under complex terrain remain challenges. That severely hinders the assessment of highway PV potential. To address these challenges, a spatiotemporal model is developed in this study to estimate the annual solar PV potential on highways over the whole Chinese territory. First, the areas of different highway segments are calculated based on highway network and highway toll stations. Second, hourly shadow area on highways created by nearby terrain is estimated based on a digital elevation model (DEM). When calculating the highway PV potential, the solar irradiation received in these shadow areas is regarded as zero. Finally, the PV potential of all lanes and emergency lanes was estimated at the prefecture-level city scale using surface radiation data and radiation assessment models. Based on the highway data with a total mileage of 143,684 km at the end of 2020, the results show that the annual PV potential is 3,932 TW and that the corresponding installed capacity is 700.85 GW, which can generate clean electricity at a rate of up to 629.06 TWh. The annual PV potential of highways in the southeast is greater than that in the northwest owing to the higher highway density in the southeast. This study provides a reference basis for highway PV construction planning and suitably assessment in each region of China for PV highway development.

1. Introduction

Although renewable energy is seemingly developing with an overwhelming tendency, the share of traditional fossil fuels was still greater than 80% of the global total final energy consumption at the end of 2019 [1]. Obviously, there are enormous challenges that must be overcome to achieve a complete global transition from traditional fossil fuels to clean and sustainable energy. Solar photovoltaic (PV) offers great feasibility and low cost in various applications to convert solar energy into electricity. PV systems can be deployed in a variety of places that receive an

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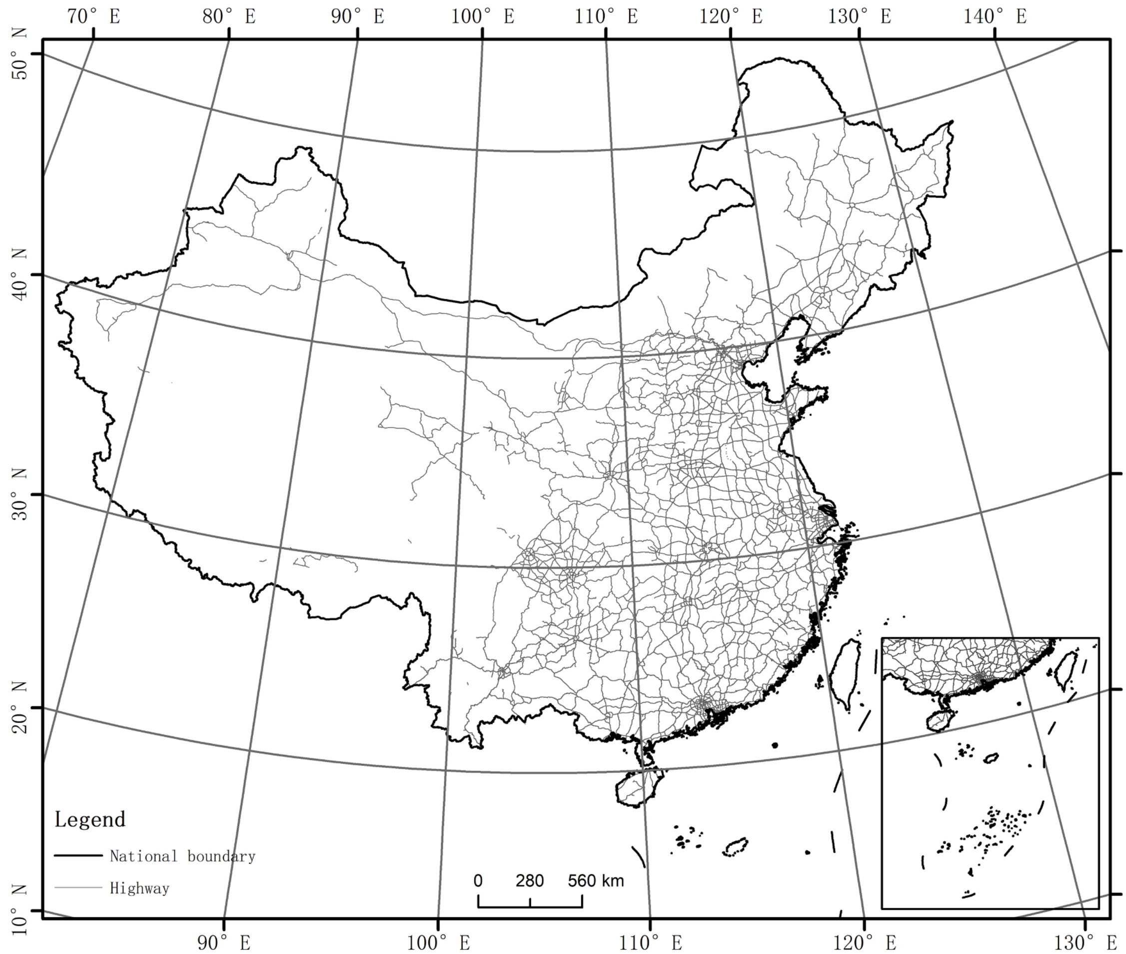

Fig. 1. Study area and highway network in China.

abundant amount of solar input.

In China, the carbon peak and neutrality goals reflect the need to reduce carbon emissions. To achieve these goals, the Chinese government has set medium- and long-term targets for a total installed PV capacity of 600 GW by 2030 and 1500 GW by 2060, respectively [2]. Although the total grid-connected installed solar power capacity reached 253.43 GW at the end of 2020 in China [3], it is still far from the planned installed PV capacity required to meet the peak carbon goal in China. Motivated by carbon peak and neutrality goals, installation locations for various kinds of solar PV systems and their application potential are being extensively examined [4,5]. Previous studies have examined the spatial distribution characteristics of solar energy in China from the perspective of PV land use suitability [6]. The shifting trend of land resources accessible for constructing solar PV systems in China has also been investigated [7]. The studies mentioned above provide a macrolevel answer to the overall PV potential in China, as well as the types of land appropriate for PV systems and their geographical distribution. However, these studies lack realistic guidance for specific PV applications, such as on rooftops and highway surface.

Converting the solar radiation received on a road into electrical energy to support traffic lighting facilities has been explored [8]. Subsequently, many researchers have continued exploring and developing solar PV systems for road surfaces and evaluating their performance [9–11]. After that, other transport facilities have also been considered in combination with PV systems. For example, PV panels have been installed on top of road tunnels [12], combined with charging stations [13], and installed on road noise barriers [14,15]. Furthermore, if a site has significant solar energy potential, highway slopes are also regarded as great places for installing PV systems [16]. In China, the first PV highway was constructed in Jinan in 2017 [17]. Despite the fact that the PV panels on the carriageways were removed after a year, the PV panels in the emergency lane remain operational [18]. The Hangzhou-Shaoxing-Ningbo Smart Highway, a superhighway incorporates PV panels, is also under construction and scheduled to open in 2022 [19] .

The high interest in PV systems for highways and other transportation infrastructures is due to the low contribution of renewable energy in the transportation sector [20]. As of 2019, oil and petroleum products still accounted for approximately 95.8% of all worldwide transportation energy usage in 2019, with renewable electricity and biofuels accounting for only 0.3% and 3.1%, respectively [1]. In addition, the transportation industry produces approximately a quarter of worldwide anthropogenic CO_2 [21]. While the transportation sector appears to be a major impediment to achieving carbon reduction targets, it may also help achieve the decarbonization goal if the use of PV systems is promoted on highways. PV panels on highways can help mitigate the urban heat island effect by increasing the supply of renewable energy, improving the energy mix, and reducing greenhouse gas emissions [10]. In addition, charging stations, highway service areas, and other traffic infrastructures can directly use the power generated by highways PV systems. Therefore, the main obstacles to PV system development and widespread implementation, including high storage costs, transmission costs, transmission losses, and grid connection costs, maybe overcome [22]. PV highways can also alleviate the mileage anxiety issue associated with electric vehicles (EVs) by providing solar energy charging stations or real-time charging options on highways [23]. Additionally, the digitalization of highways is proceeding quickly, and renewable energy resources are crucial subcomponents of these digital

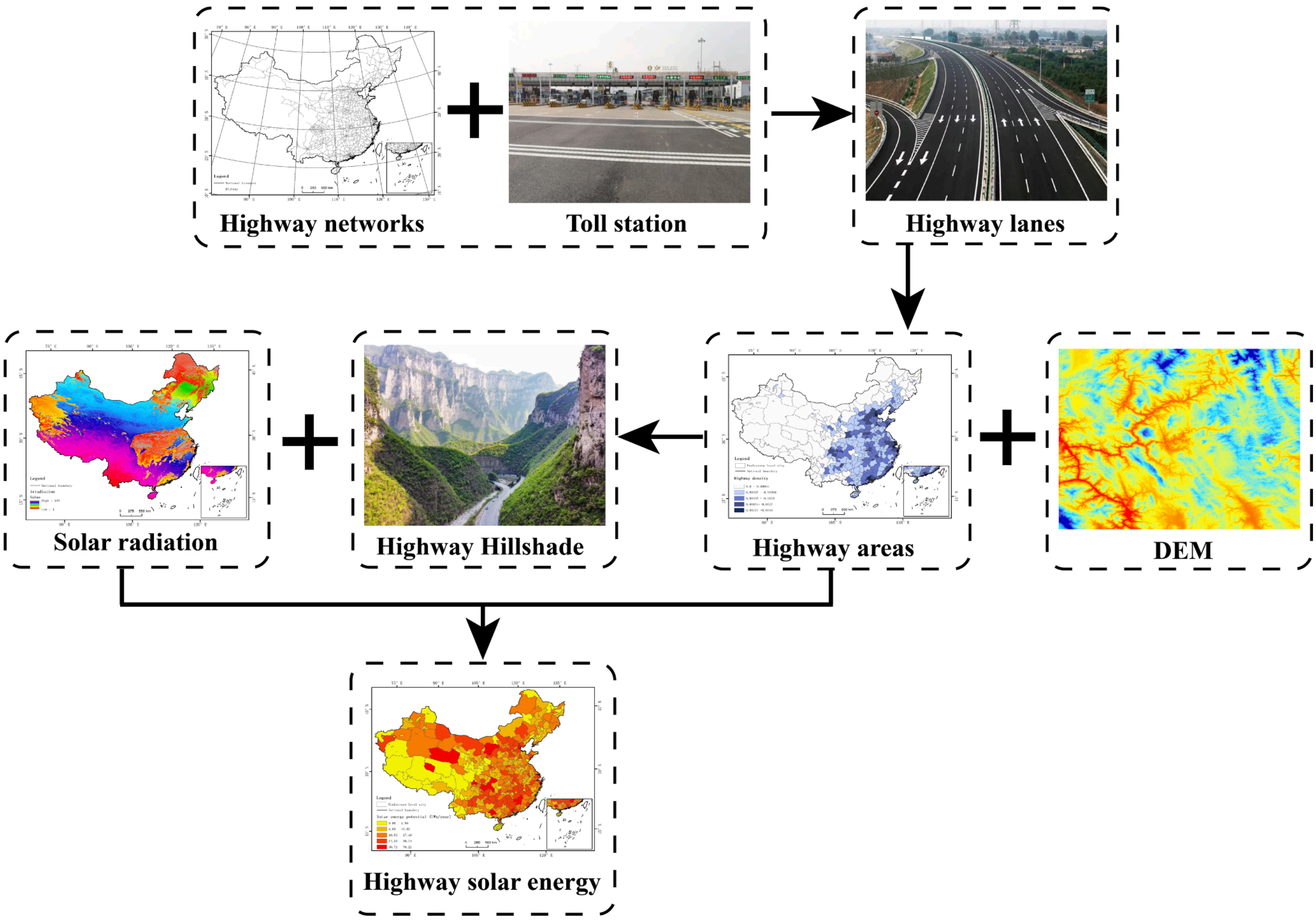

Fig. 2. Overall research framework (image credit: Baidu Images).

systems [24]. Therefore, PV highways can also promote the development of highway digitalization and intelligent cities. In comparison to installing PV panels on top of highway slopes and tunnels, installing PV panels on highway surfaces requires no additional land resources and does not harm nearby natural systems [25]. Highways are normally managed by the government as public land use, thus when PV highways are built, there will be a high level of convenience and few obstructions [16].

The total mileage covered by the highways in China exceeds 140,000 km, ranking 1st in the world [26]. As an important transportation infrastructure, highways are spread all over the country and connect different cities and regions. Even assuming that all highways are 15 m wide, Chinese highways could provide abundant areas for the deployment of PV systems [27]. Another distinctive feature of Chinese highways is that their distribution is denser in the southeast than in the northwest. Therefore, the construction of highway PV systems in China could help to alleviate the energy demand issues in southeastern and northwestern China, where there is a significant mismatch between the installed solar PV capacity and the energy demand [28]. Although some studies have assessed the highway solar energy potential in China [13, 27], these studies were conducted based on four conditions: 1) all highways in China were assumed to have the same number of lanes; 2) tunnel regions were not excluded from highway radiation calculations; 3) the surrounding terrain was assumed to have no effect on the solar radiation received by the highway surface; and 4) the total solar radiation received by each highway was assumed to be equivalent. However, passenger and freight traffic vary significantly in different areas, and the number of highway lanes can highly vary by region [29]. Tunnel segments and shadow areas on the highway surface caused by the surrounding terrain also need to be considered when calculating the solar energy potential of highways. Furthermore, these studies did not go into detail regarding the geographical distribution characteristics of the highway PV solar energy potential and the suitability for planning at the province and prefectural city scale.

To the best of our knowledge, this is the first study to consider the shading of highway surfaces by the surrounding terrain at the hourly scale and combine this information with hourly radiation data to precisely assess the potential of PV highways in China. The main contributions of this study are as follows: 1) the area of Chinese highways was accurately calculated by manually measuring the number of lanes between adjacent toll stations on each section of each highway; 2) before calculating the solar energy potential of highways in China, highway attribute features and DEM were used to remove the tunnel segments and the hourly shaded area of the highway surface caused by the surrounding terrain, respectively; 3) Adopted a month-representative day strategy to calculate the hourly shaded areas on the highway surface for each region throughout the year to decrease the computational costs; and 4) the spatial distribution characteristics and the planning suitability of China's PV highways have been analyzed at a prefecture-level city scale. The remainder of this study is structured as follows. The associated features of the study area and fundamental data are introduced in Section 2. The proposed method is comprehensively presented in Section 3. Section 4 gives the results of this study. The study results and a discussion are presented in Section 5.

2. Study area and materials

2.1. Study area

China is located in the eastern of the Eurasian continent, with

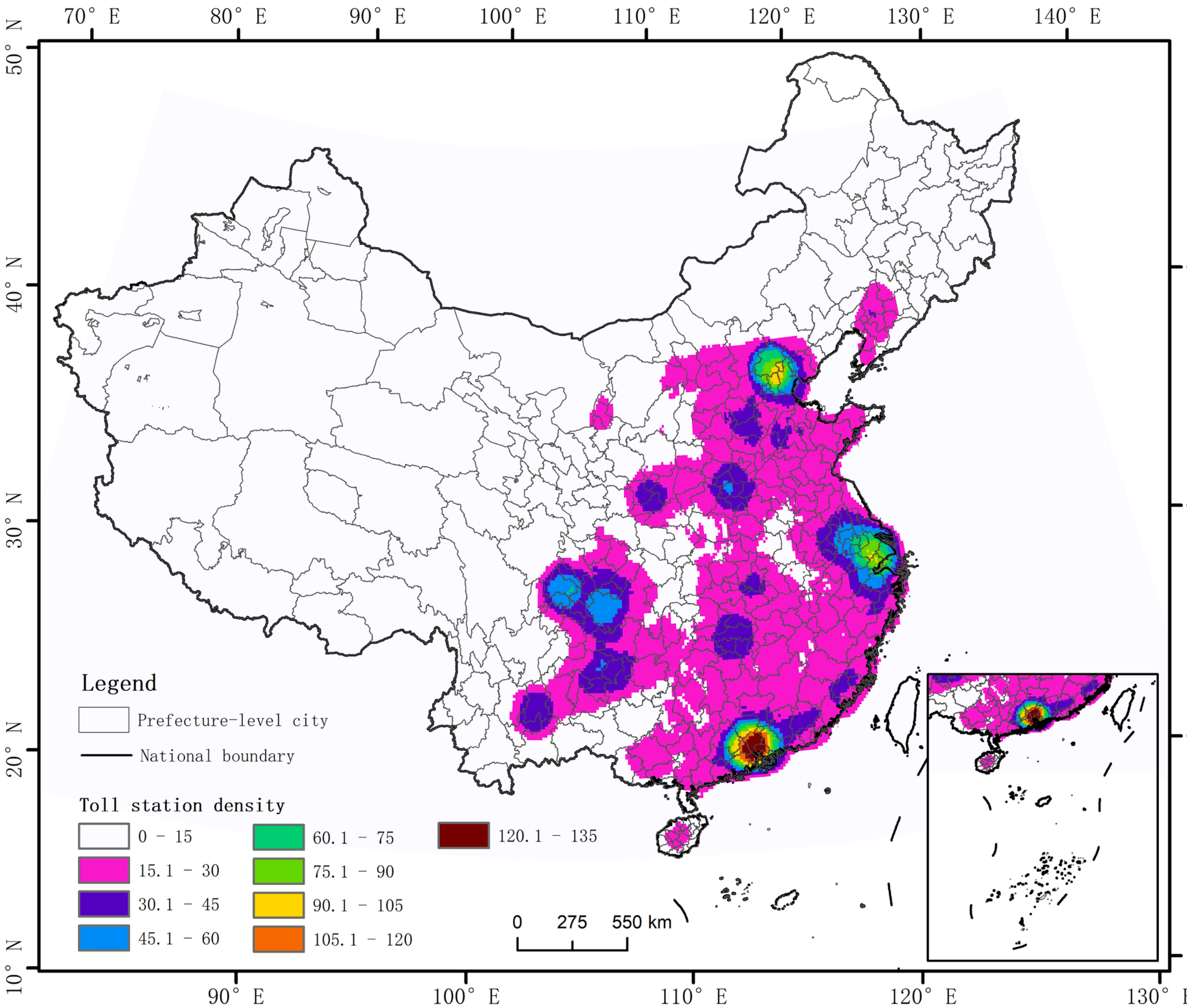

Fig. 3. Spatial pattern of highway toll stations in China.

longitude and latitude range from 73° 33'E to 135° 05′ E, and 3° 51'N to 53° 33′ N, respectively (Fig. 1). The large latitudinal differences and the unique land and sea features result in notable variations in radiation potential across different regions in China [6,30]. The overall highway mileage in China exceeded 140,000 km as of 2018 [31]. Economic development has been considerably aided by China's robust, dense, and convenient highway transportation network infrastructure. The percentage of fossil fuels consumed by the automobile sector is projected to continue to rise [32]. Therefore, fuel vehicle emissions will cause further deterioration of the air environment. Fortunately, the Chinese highway network offers abundant space for solar PV systems to be installed. If highway PV systems are used to create electricity, carbon emissions could be greatly reduced, and the generated clean electricity could be employed in intelligent transportation industries, such as for electric automobiles.

2.2. Basic data collection

In this study, the highway network was obtained from OpenStreetMap (OSM). OSM is a crowdsourced data platform that supplies diverse vector data for features such as road networks, rivers, and administrative divisions [33]. Chinese highway network can be directly extracted according to administrative regions and road rank attribute information (data for Taiwan are not yet available). The obtained highway dataset contains information such as the road name, whether a tunnel is present, whether a bridge is present, and other attribute information. Highway toll stations are an essential data source for this study and were used to calculate the number of lanes in each highway section and the area of highways. A Python script was used to gather highway toll stations from Baidu Map (https://lbsyun.baidu.com). Data from a total of 12,221 highway toll stations in China were obtained. A digital elevation model (DEM) is a digitized representation of the topographic surface of the Earth. It uses an ordered array of numbers to represent the elevation of the ground. The Earth Observing System Data and Information System (EOSDIS) provides DEM data with a 12.5 m resolution, which was utilized to study the dynamic properties of shaded areas of the highway impacted by the surrounding terrain. A surface solar radiation dataset with 5 km spatial and hourly temporal resolution was the basis for accurately estimating the highway radiation potential. Tang produced surface solar radiation data from 2007 to 2014 based on data collected at meteorological observation stations and remote sensing data [30]. This radiation dataset was downloaded from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn) for use in this study.

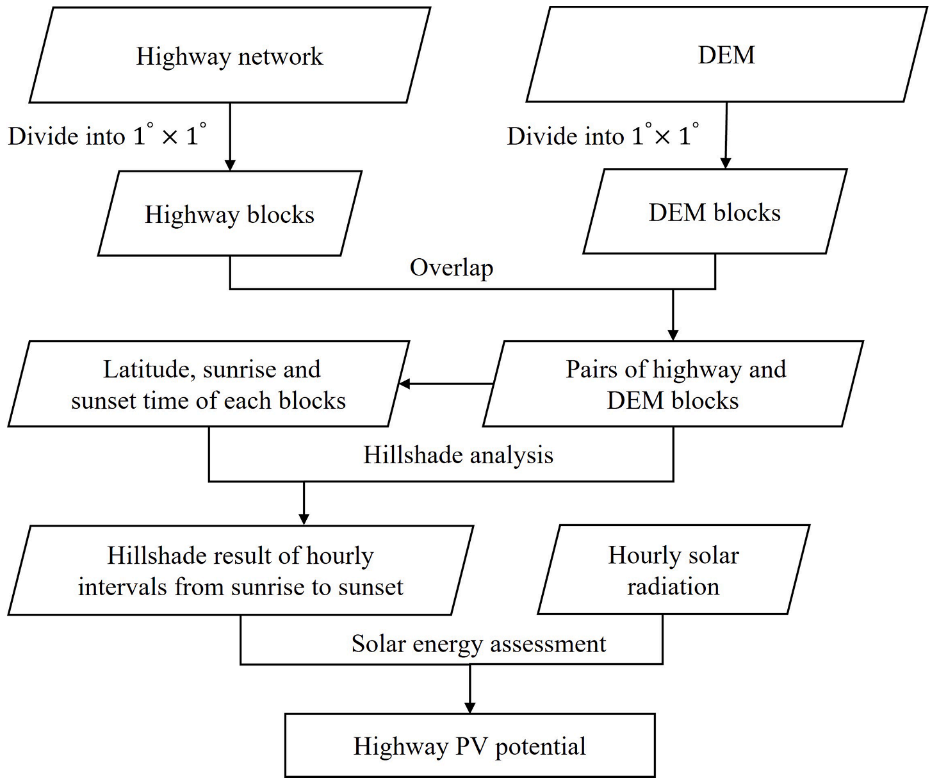

Fig. 4. The technical process of the highway shadow analysis.

3. Methodology

In this study, highway PV potentials was quantified as follows. First, utilizing highway toll stations and Google Earth Pro (GEP), the number of lanes along different segments of highways was manually determined. Highway engineering construction standards were to calculate highway widths in the corresponding segments. Second, the shadow areas on the highway surface created by the surrounding terrain, i.e., Hillshade, were estimated hour by hour. These shaded areas were considered while evaluating the solar energy potential. Third, the PV potential of all lanes and emergency lanes on highways was assessed using irradiance data. Finally, statistics at the prefecture-level city scale were obtained for the solar energy potential, PV installation capacity, and generated power of PV highways in China. Fig. 2 shows the overall flowchart of this study.

3.1. Identify the number of highway lanes

Obtaining the highway area is a prerequisite for evaluating the PV potential of highways. However, the OSM data do not contain the area information for highways, and additional effort is required to calculate this area based on highway lane characteristics. Although the technical standards of highway engineering regulate the width of highway lanes [34], obtaining comprehensive highway network data with lane number information is extremely difficult. To quantify the number of lanes conveniently and precisely for all highways in China, it was assumed that the number of highway lanes between neighboring toll stations is fixed. Then, artificial sampling was used to acquire the number of highway lanes in China based on highway toll stations and GEP. As noted in Section 2.2, 12,221 highway toll stations were identified from Baidu Maps data. However, extra data processing was required for the initial toll stations to remove redundant information. Because there may be multiple exits or enters when a vehicle exits or enters the highway, there may be multiple corresponding toll stations to regulate a highway segment. However, only one toll station is required to quantify the number of highway lanes in each corresponding highway segment.

Therefore, the redundant toll stations were eliminated according to their names and distances. If the name of a toll station was the same or the distance between stations was within 2 km, only one toll station was retained. After preprocessing, a total of 8,794 highway toll stations were reserved. The toll stations were then linked to GEP, which manually identifies the number of highway lanes in different highway segments. No toll stations on the highways in the provinces of Tibet and Hainan were identified in this process. Since the government fosters regional growth by granting free access to highways there, no highway toll stations are present in Tibet [35]. There are also no highway toll stations in Hainan because highway tolls are included in vehicle fuel prices [36]. Therefore, manual sampling points were established at 5 km intervals along highways in Tibetan and Hainan provinces. In Tibet and Hainan, a total of 126 highway sampling points were manually labeled.

Ultimately, 8,920 valid highway lane sampling points were established. Obtaining a good representation of the spatial characteristics of highway toll stations in China on a small-scale map is difficult due to the dense density of highway toll station sites. Therefore, for visualization purposes, the number of toll stations was converted to a kernel density. Fig. 3 depicts the spatial distribution characteristics of highway toll stations in China. It is important to note that highway lane numbers are not based on the exact location where a toll station is located because the number of lanes near a station is often temporarily increased to facilitate vehicles entering and exiting the highway. Therefore, the number of highway lanes was generally determined approximately 2–5 km from each toll station to ensure that the number was representative of the actual number of lanes along the road segment. All segments of highway lanes were obtained using ArcGIS after determining the number of highway lanes based on information from nearby toll stations. Furthermore, emergency lanes are primarily located on both sides of highways for engineering rescue, fire rescue, medical rescue, or police to provide emergency services and support the travel of emergency vehicles. In contrast to ordinary highway transportation lanes, the emergency lane receives less shadowing from vehicles because it is rarely used. In addition, the emergency lane is used by fewer heavy-duty trucks. Therefore, installing solar panels in emergency lanes is a safer and more practical alternative than installing them in typical highway lanes. Moreover, according to the technical standard of highway engineering, a single lane is 3.75 m wide, and an emergency lane is generally 2.5 m wide [34]. Therefore, the widths of all segments of highways and emergency lanes can be confirmed based on this technical standard. Then, the area of highways can be calculated using the calculated mileage and width information.

3.2. Shading analysis of highways

The shade of the highway surface generated by the surrounding terrain is also considered while assessing the solar radiation received by each highway in this study. The solar position dynamically changes during the day. Therefore, as the sun moves, the shadow area on the highway surface changes. If the solar radiation received by the highway is to be effectively analyzed, the dynamics of highway surface shadows must be considered. However, calculating the dynamic features of highway surface shadows in real time requires vast computational resources and time. Therefore, to more accurately and efficiently measure the real solar energy received by the highway surface in this study, the shadow area on each segment of the highway is estimated hourly. Furthermore, Chinese highways are dispersed over a broad area, with 60-degree longitude deviations. Due to large longitudinal differences, there are significant temporal disparities in different parts of China, with ramifications for how accurate highway shading analysis can be performed at a national scale. Therefore, to avoid the impacts of time differences, the DEM and highway network are separated into multiple blocks, each of which is $1^\circ \times 1^\circ$ in size. This highway and DEM layers are overlayed after splitting the DEM and highway grids to exclude DEM blocks that do not contain highway segments. The goal of this approach is to reduce the number of calculations needed. Finally, in this investigation, 615 pairs of DEM and highway data blocks were obtained in the study area. Hillshade analysis was then carried out for each block using ArcPy. The Hillshade tool can create shadow relief from a surface raster by considering the illumination source angle and shadows. The shaded raster values ranged from 0 to 255, and raster cells in shadow areas were assigned a value of zero [37]. In this study, a highway segment was considered to be shadowed if the shaded raster cell value for the highway coverage area was 0. During the sunrise and sunset periods in each block, Hillshade analysis was performed hourly for each pair of block data. The technical process of highway shadow analysis is shown in Fig. 4.

Estimating the daily shadows of highways throughout the year in China requires a considerable amount of time. Therefore, a month-representative day strategy based on a day in the middle of each month was adopted for highway shading analysis. During the shading analysis process, the zenith angle and altitude of sun are the core parameters that influence the shadow area on highways. Using latitude information from the DEM, the zenith angle, altitude, and hour angle of solar radiation in each block area were calculated. The highway shadow area in each block was then estimated hourly throughout the day. In this study, the Hillshade tool in ArcGIS was used to perform highway shading analysis.

The hourly solar azimuth and latitude, the z-factor, and the sunrise and sunset times each day of the month were needed before determining the hourly shadow regions in each block of highway. The z-factor was directly acquired based on the latitude of each DEM block [37]. It is a scaling factor used to convert observed elevation values. Other factors, such as solar azimuth and latitude, as well as the times of sunrise and sunset, were estimated using associated mathematical models. First, solar declination, which is the angle between the solar rays and the plane of the Earth's equator, was calculated. Equation (1) shows the formula for calculating solar declination.

$$\delta = 23.45^\circ \times \sin\{360^\circ \times [(284 + n)/365]\} \tag{1}$$

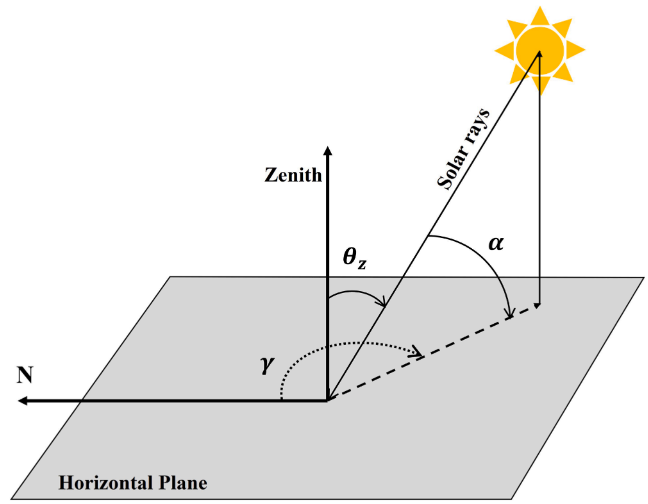

Fig. 5. Schematic diagram of the relationship between incident sunlight and the Earth's surface, where θ_z is the solar zenith angle, α is the solar altitude angle, and γ is the solar azimuth angle. Revised by [38].

where δ is solar declination, n is the nth day of the year, and 23.45° is the tilt angle of the Earth. Next, the solar hourly angle needs to be calculated. On Earth, at the same longitude and different latitudes, the corresponding hour angle of the sun will be the same. The Earth spins 360° every 24 h. Hence, the corresponding hour angle deviation is 15° per hour. The hourly solar angle equation is shown as follows:

$$\omega = 15^\circ (t_s - 12) \tag{2}$$

where ω is the solar hour angle and t_s is the solar time.

Next, the solar zenith was calculated with the following equation:

$$\cos\theta_z = \cos\delta \times \cos\varnothing \times \cos\omega + \sin\delta \times \sin\varnothing \tag{3}$$

where θ_z is the solar zenith and $\varnothing$ is the latitude of the block area acquired from the corresponding DEM.

The solar altitude angle is the complement of the zenith angle. Therefore, the solar altitude calculation equation is as follows:

$$\alpha = 90^\circ - \theta_z \tag{4}$$

where α is the solar altitude angle.

The solar azimuth is the angle measured in a clockwise direction in reference to the northerly direction of a target as the starting point; the incident direction of the sun is the finishing point. The corresponding formula is as follows:

$$\gamma = \cos^{-1}[(\sin\alpha \times \sin\varnothing - \sin\delta)/\cos\alpha \times \cos\varnothing] \tag{5}$$

where γ is the solar azimuth. Fig. 5 illustrates the related parameters.

The sunrise equation can be used to calculate the times at which sunrise and sunset occur based on the obtained solar declination and latitude in specific block areas [39].

$$\cos\omega = -\tan\varnothing \times \tan\delta \tag{6}$$

Based on the above formulations, the hourly solar azimuth and solar altitude were acquired. The sunrise and sunset times on representative days were also acquired based on the equation above. Then, the shadows in each highway block at different times over the course of one year were calculated.

3.3. Estimation of PV potential on highways

After acquiring the hourly highway shadow areas, the amount of radiation that is received on the highway surface can be calculated by superimposing irradiation data with the same time resolution. According to previous research, the solar radiation received by ground features

Table 1
Statistical results for Chinese highway lanes and areas.

Lanes	Width (m)	Mileage (km)	Tunnel (km)	Areas (km^2)
4	20	48,438	6,180	967.3
6	27.5	49,392	7,164	1,354.1
8	35	40,984	3,363	1,430.8
10	42.5	4,846	312	205.6
12	50	24	–	1.2
Total	–	143,684	17,019	3,957.4

such as flat roofs and roads in the same area is very similar to the solar radiation on the natural surface. Therefore, the solar radiation on a highway is equivalent to the surface solar radiation at the land surface in China. First, solar irradiation data from 2007 to 2014 were preprocessed. However, only the solar irradiation data for 2014 and 2009 are relatively complete, and datasets for the remaining years have many missing values. Therefore, the hourly radiation data from 2009 and 2014 are averaged as the radiation data source for estimating the solar radiation levels along regional highways in China. Then, the shading analysis results are combined with hourly irradiation data to calculate the hourly solar energy received by each highway block. The annual solar energy received by the highways in each highway block can be acquired through the summation of all calculated hourly solar energy potential. Furthermore, highway tunnel segments cannot receive solar radiation. When calculating the total solar energy potential of highways, the solar energy received by tunnel segments should be subtracted to achieve a more precise solar energy potential estimate. The tunnel segments on the highway can be directly identified from the highway network based on the attribute information.

To calculate the highway PV potential for installed capacity and electricity generation, the solar panels installed are assumed to be 1 m × 1 m in size with a rated power of 200 W [40]. Equations (7) and (8) are used to calculate highway PV power generation and the installed capacity.

$$E_P = P_{AZ} \times H \times K \tag{7}$$

where E_P is the power generation of a PV highway, and P_{AZ} is the installed capacity of a PV highway. K is the overall performance coefficient of a solar PV system, with a general value of 0.8 [41]. H is the average number of peak sunlight hours for the solar PV system, and can be calculated based on the solar energy potential of highways.

$$P_{AZ} = P \times N \tag{8}$$

where P is the rated power of a single solar panel, and N is the number of solar panels. The rated power of the PV system in this study is 200 W/m^2. Therefore, N is the area of the Chinese highways.

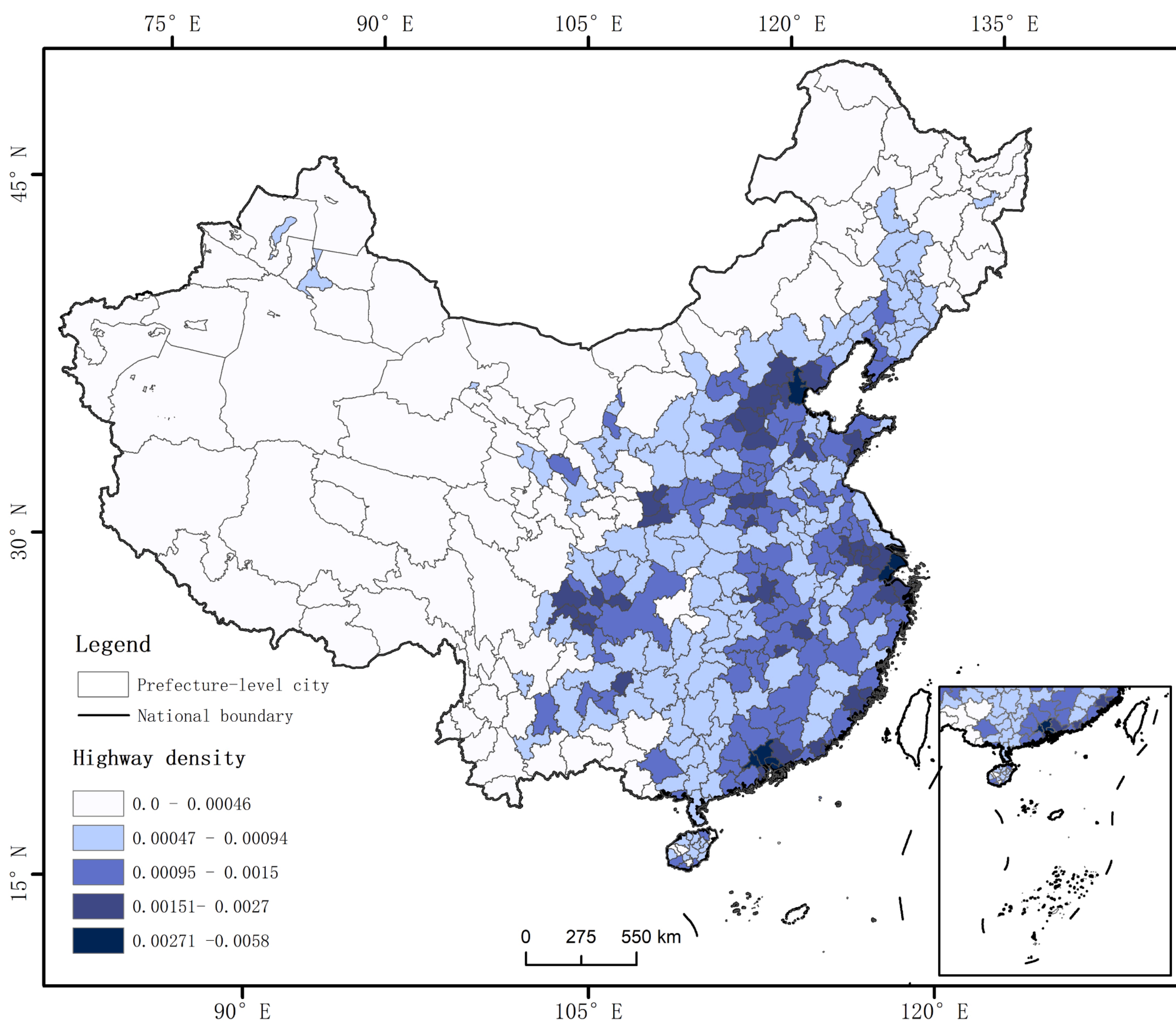

Fig. 6. The prefecture-level city highways area in China as a percentage of the administrative area of the city.

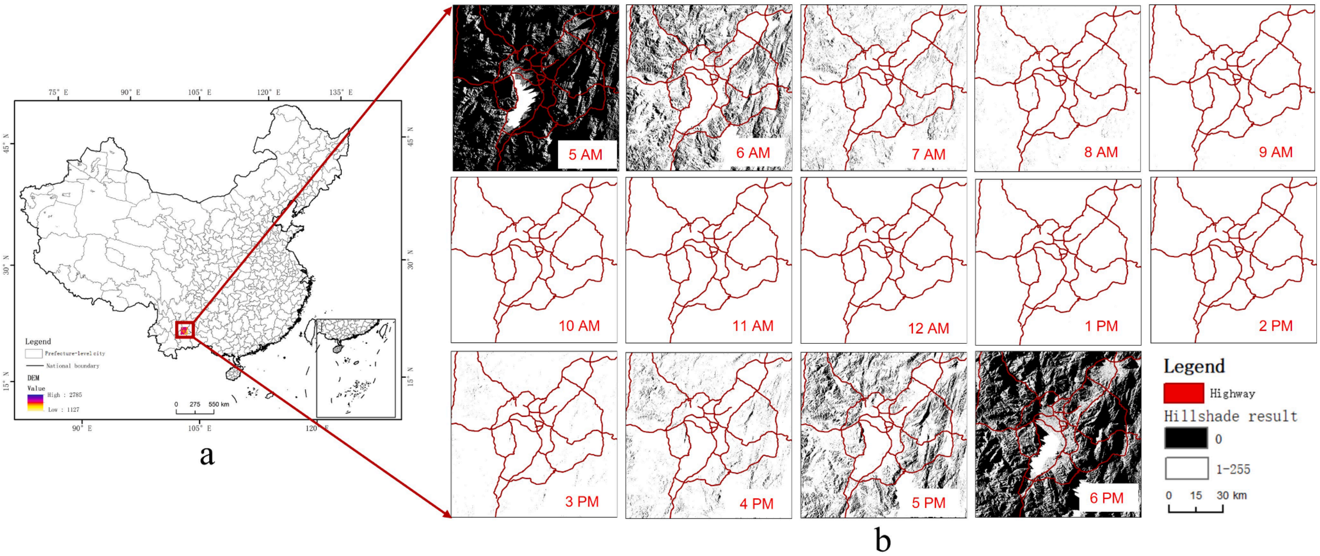

Fig. 7. The dynamic characteristics of highway shadows in the 65th block zone on July 15, 2020. (a) depicts the locations of block regions, and (b) depicts the shadow variations from sunrise to sunset in the corresponding region in the red box in (a).

4. Results

4.1. Estimated the area of highways in China

The number of lanes and area of highways in China were determined based on the approach detailed in Section 3.2. Table 1 shows the statistical results regarding the lanes and areas of Chinese highways.

According to the results of the Chinese highway lane and area quantification, the total mileage and area of Chinese highways in 2020 were 143,684 km and 3,957 km^2, respectively. Overall, 8-lane highways account for the longest mileage, reaching 6,180 km. A total of 98.1% of China's total highway mileage is composed of 4-lane, 6-lane, and 8-lane highways. In China, the entire mileage of 12-lane highways is only 24 km. It is worth noting that the tunnel mileage on 4- and 6-lane highways is the longest among highways with different lane numbers in China. In addition, as the number of highway lanes increases, the number of tunnel miles on highways decreases. Notably, majority of 8-lane, 10-lane, and 12-lane highways in China are constructed in the eastern and southeastern areas. These areas are characterized by dense populations and vigorous industrial activity. The demand for passengers and cargo freight is very high there, and the terrain of these areas is dominated by plains and hills. Therefore, the highways in these areas usually have more lanes and fewer tunnels.

Fig. 6 shows the spatial distribution of prefecture-level city highway areas in China as a percentage of the administrative area of the city. Because the area of the administrative region of each prefecture-level city in China varies so significantly, it is impossible to accurately reflect the spatial distribution of highways solely based on the mileage of each city. Therefore, the ratio of the highway area in each prefecture-level city in China is calculated to visualize the spatial distribution

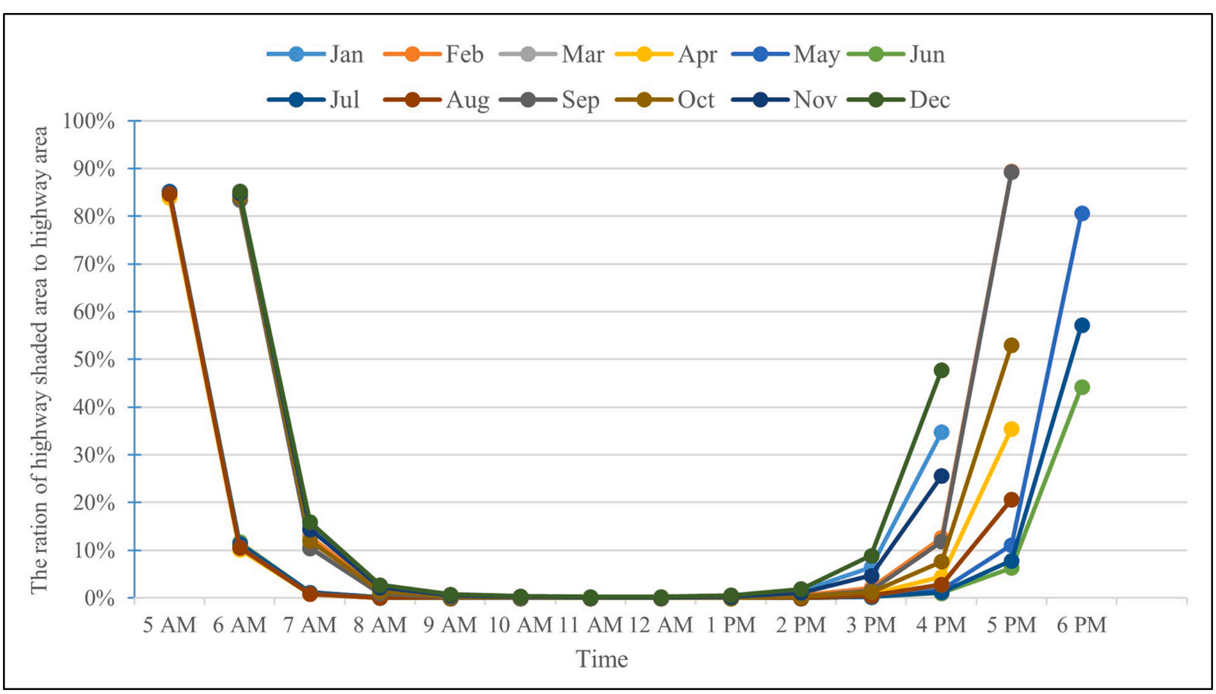

Fig. 8. The characteristics of intra year dynamic variations in the ratio of the total highway shadow area to the highway area in the 65th block.

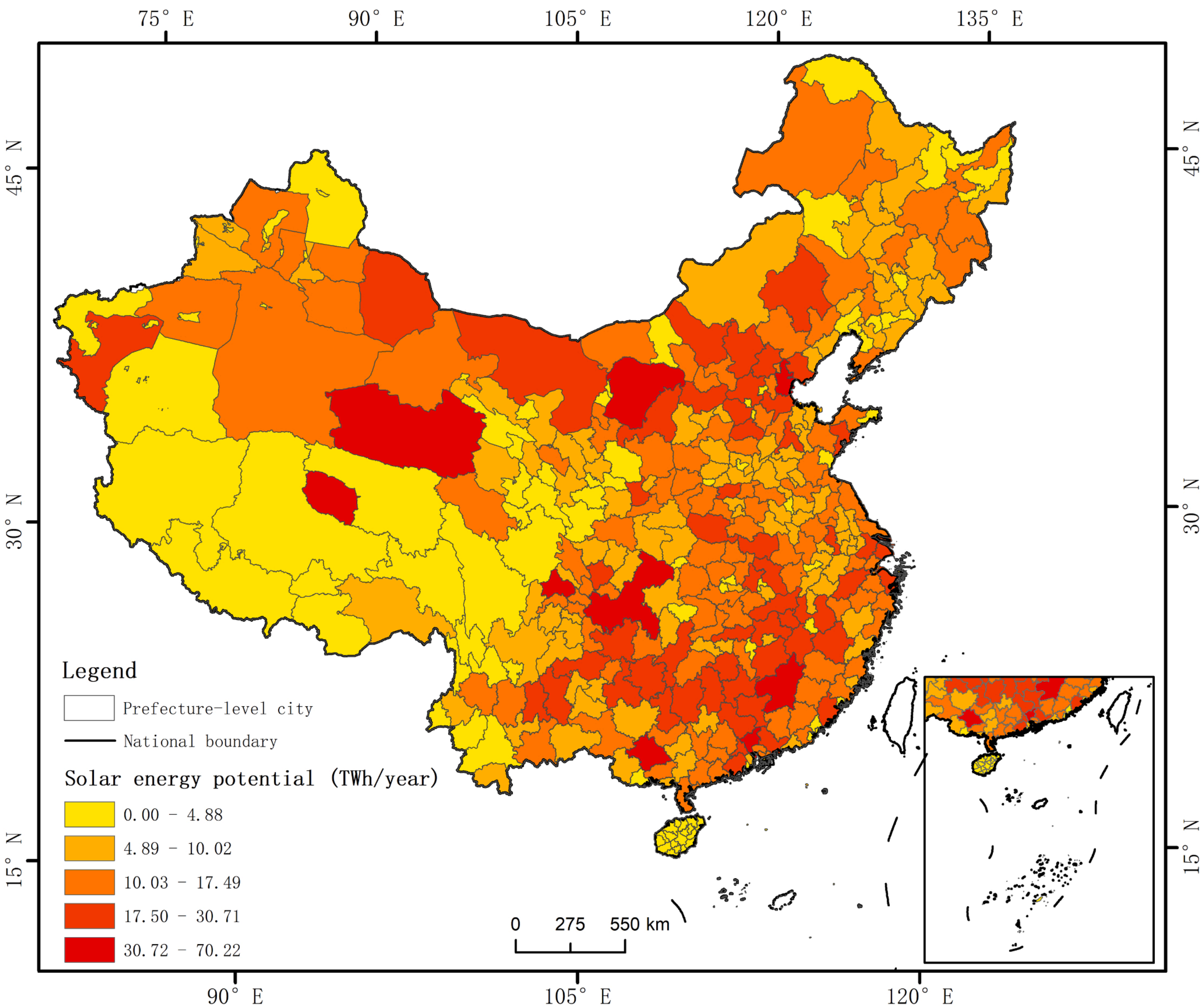

Fig. 9. The annual solar energy potential of Chinese highways at the prefecture-level city scale.

characteristics of Chinese highways. As illustrated in Fig. 6, the cities in central-eastern and southeastern China have the highest highway area proportions. The highway area proportions in northern, northwestern, and southwestern cities in China are relatively low. These areas have sparse populations, fewer industrial activities, and less demand for passenger and freight transport. These factors are coupled with the long distances between cities in these regions and the huge cost of highway construction. Therefore, the highway area proportions are substantially lower than that the proportions in the southeast.

4.2. Characteristics of highway shadows in China

The solar energy potentials of PV highways are influenced by shadow areas on the highway surface created by the surrounding terrain. In this study, a total of 615 paired blocks of DEM and highway data were used to calculate the hourly shaded areas of highways throughout China, as described in Section 3.2. A mountainous area with varied terrain was chosen for this study to demonstrate the dynamic changing features of the shadow areas on highways over the course of a day. Fig. 7 shows the dynamic highway shadow areas from sunrise to sunset for the 65th block in southwestern China.

Then, statistics for the areas of highway shadow areas in Fig. 7 (a) from sunrise to sunset throughout the year were calculated. The ratio of highway shadow areas to highway areas was determined to assess the extent of highway shadows effects at different times. The statistics results are shown in Fig. 8.

Figs. 7 and 8 show that there is essentially no shadow on the highway in the 65th block area after 9 AM and before 2 PM. The shaded area of the highway is greatest during the hour after and before sunrise or sunset, accounting for up to approximately 90% of the highway area. Between one and two hours before and after sunrise or sunset, the highway shadow area decreases rapidly, with the shadow area accounting for approximately 10% of the highway area. Because block 65th is a mountainous area, and the highway receives more influence from the surrounding terrain than do the plains and low hills in central and eastern China. Therefore, in the central and eastern regions of China, the shaded area of the highway also decreases rapidly as the time interval between sunrise and sunset periods increase. In addition, the rate of shadow area reduction in these areas is faster than the change in block 65. Generally, the intensity of solar radiation received by a highway is low around sunrise and sunset. Therefore, the potential of solar energy lost during these periods is small, even if the highway is shadowed by surrounding terrain.

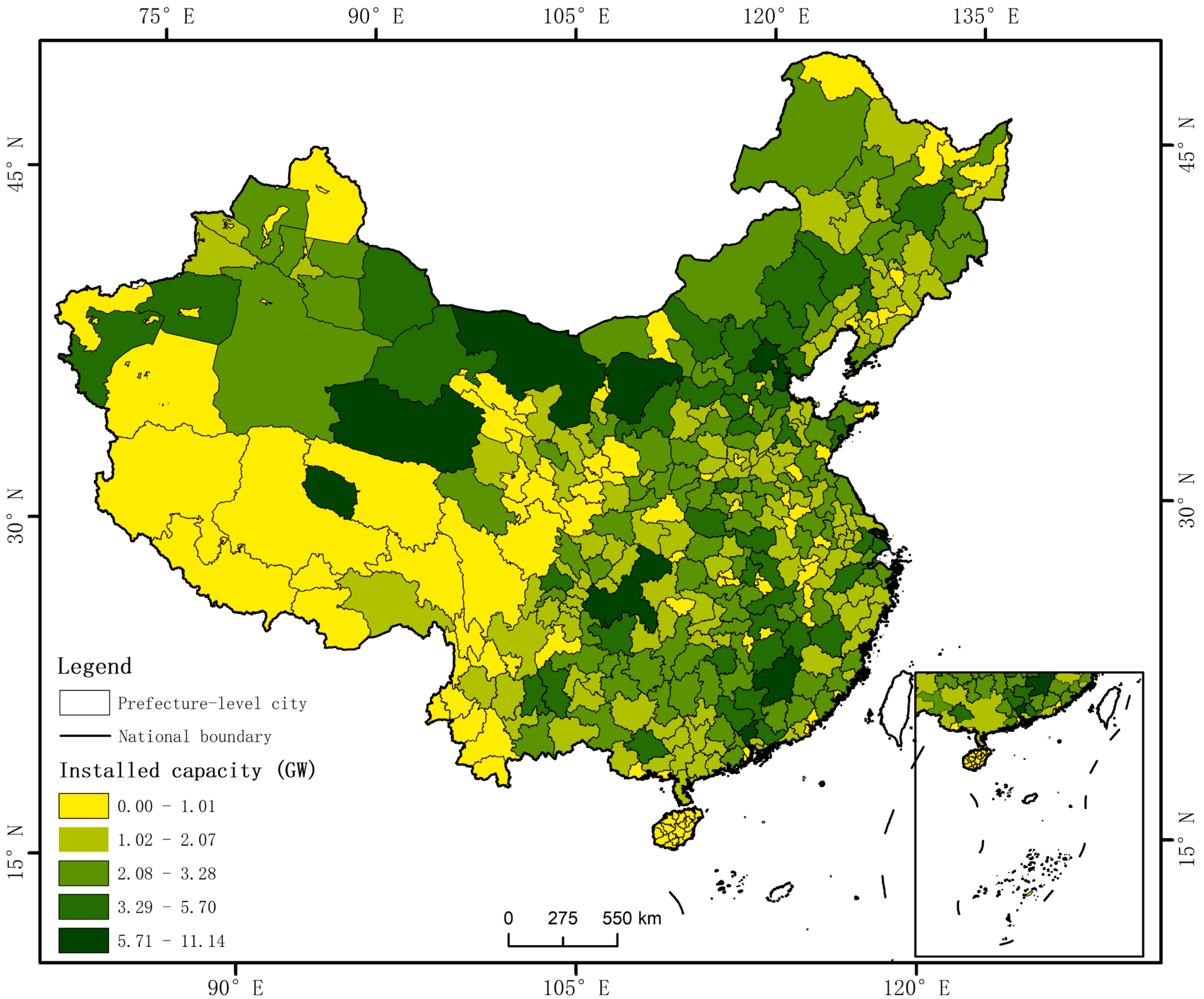

Fig. 10. The spatial distribution characteristics of the installed PV highway capacity in China.

4.3. Assessment of the solar energy potential of highways in China

After acquiring the highway areas and hourly shadow areas for each block, the hourly solar energy potential of highways in the corresponding blocks can be calculated. By summing the hourly solar potential of each block of the highway and subtracting the solar energy received in highway tunnel segments, the annual solar potential of the highway can be determined. The annual solar energy potential of the entire Chinese highway is obtained by summing the annual solar radiation potential of the 615 blocks based on the above method. Fig. 9 shows the distribution of the annual solar energy potential of Chinese highways in cities at the prefecture-level.

According to the obtained results, the highway solar energy potential in China is 3,932 TW. Fig. 9 shows that cities with high highway solar energy potential is mostly located in the northwest, north, and south-central parts of China. Notably, cities in these regions have larger administrative areas and more highway mileage than cities in the southeast. Furthermore, most of these cities are in moderate continental climate zones with lots of sunshine and little rain, which means they have higher solar radiation potential. A comprehensive analysis the highway solar radiation potential in each prefecture-level city is conducted in conjunction with the corresponding administrative region. The spatial distribution characteristics of the per square kilometer highway solar energy potential in each prefecture-level city are similar to those in Fig. 6. That is, the highway solar energy potential per square kilometer in the north, northwest, and southwest regions of China is lower than that in the southeast.

4.4. Assessment of the PV potential of highways in China

The installed capacity and power generation of PV system are important parameters for evaluating the potential of these systems. According to the approach described in Section 3.3, the installed PV capacity and power generation potential of PV highways in China can be calculated based on the highway solar energy potential. If solar PV panels are installed on all lanes of Chinese highways, the corresponding capacity would reach 700.85 GW, and power generation would reach 629.06 TWh. Figs. 10 and 11 show how installed capacity and power generation associated with PV highways in China are distributed across the country.

If PV panels are only installed in the emergency lane of highways in China, the PV highway installed capacity will reach 82.59 GW, and power generation will reach 75.40 TWh. In terms of spatial distribution characteristics, several cities in central and northern China have the highest potential for both installed PV capacity and power generation. However, the mileage of highways within cities varies substantially due

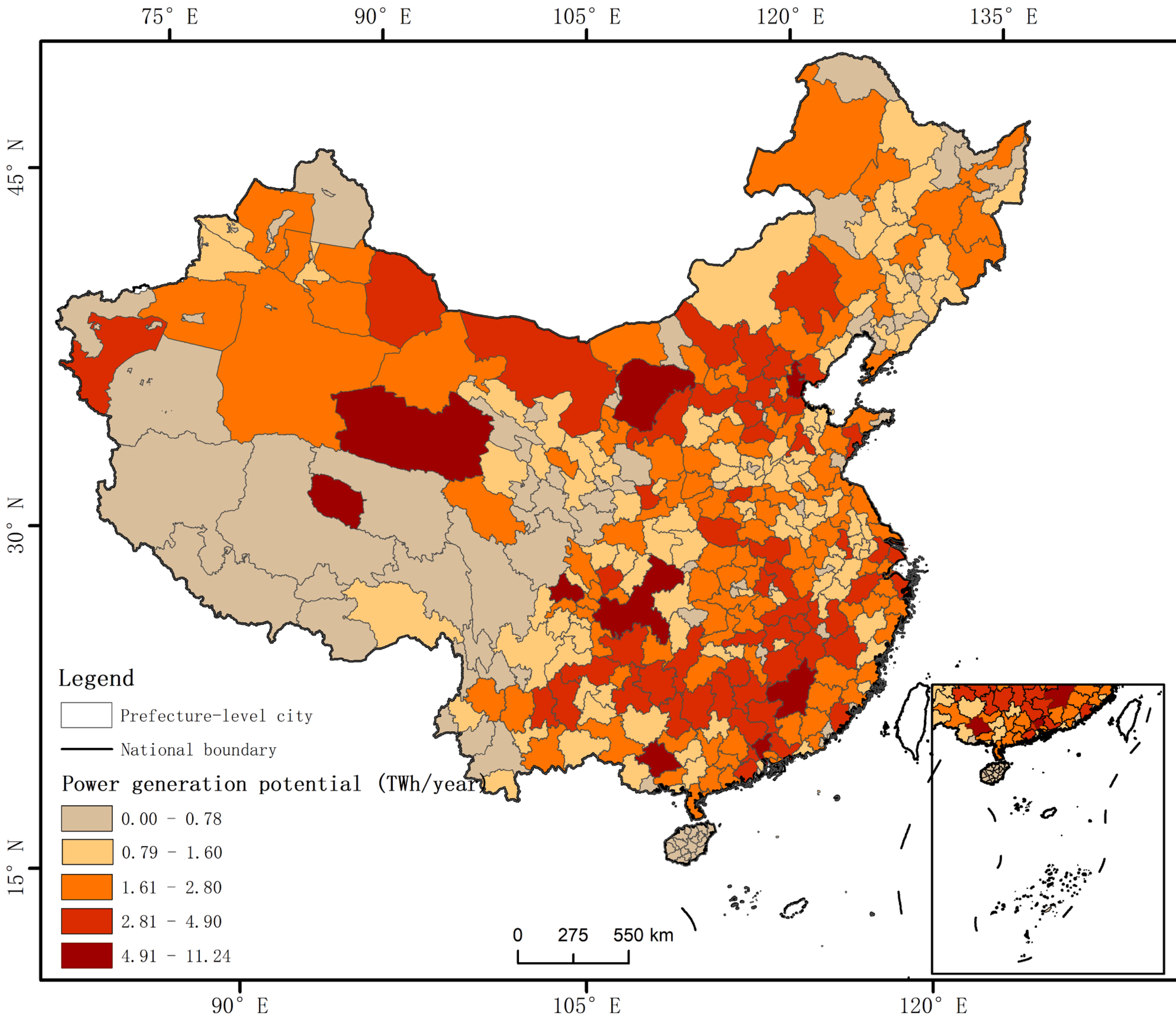

Fig. 11. The spatial distribution characteristics of the PV highway power generation potential in China.

to the considerable variances in the administrative areas of different cities in China. Therefore, the density of PV highway power generation in each prefecture-level city is calculated in this study. That is, the PV highway power generation in a city is divided by the area of the city's administrative district. The spatial distribution of the annual density of generation along PV highways in prefecture-level cities in China is shown in Fig. 12.

As illustrated in Fig. 12, the cities with the highest densities of PV highway generated electricity are primarily situated in eastern China. The seven cities with the highest PV highway generated electricity densities are Shanghai, Jiaxing, Guangzhou, Dongguan, Shenzhen, Hong Kong, and Foshan. This mapping result suggests that the highway area is an important factor that influences the effectives of PV highways. Eastern Chinese cities often have high highway densities and more highway lanes than those in western and northern China. In addition, cities in southeastern China are densely populated with concentrated industrial and commercial activities, so there is a huge demand for energy there. Therefore, PV highways have greater application potential in the eastern region of China.

5. Discussion and conclusion

5.1. Discussion

Although the highway shadow areas caused by terrain are considered when estimating the highway solar PV potential at the hourly scale, other factors, e.g., the shadows cast by road noise barriers, roadside trees, and highway guardrails are not considered. Because of the constraints posed by the availability of data and the expenses involved in collecting data, carrying out an evaluation of this kind is a challenging endeavor. Additionally, when building highways, the natural ground shape is modified to accommodate the construction requirements, such as during the placement of bridges in valleys and excavation in lower mountains. It is necessary to ensure that the slope of the highway conforms to engineering standards. However, these altered surface morphologies caused by construction cannot be characterized in the original DEM data.

According to the findings of this research, PV highways in China offer a significant amount of PV potential. However, PV highways are not yet being promoted or used to a large extent at this time. Installing PV panels on highway surfaces is associate with many technical challenges that need to be overcome. For example, how PV panels can withstand heavy-duty vehicles, and how PV panels are effectively embedded in

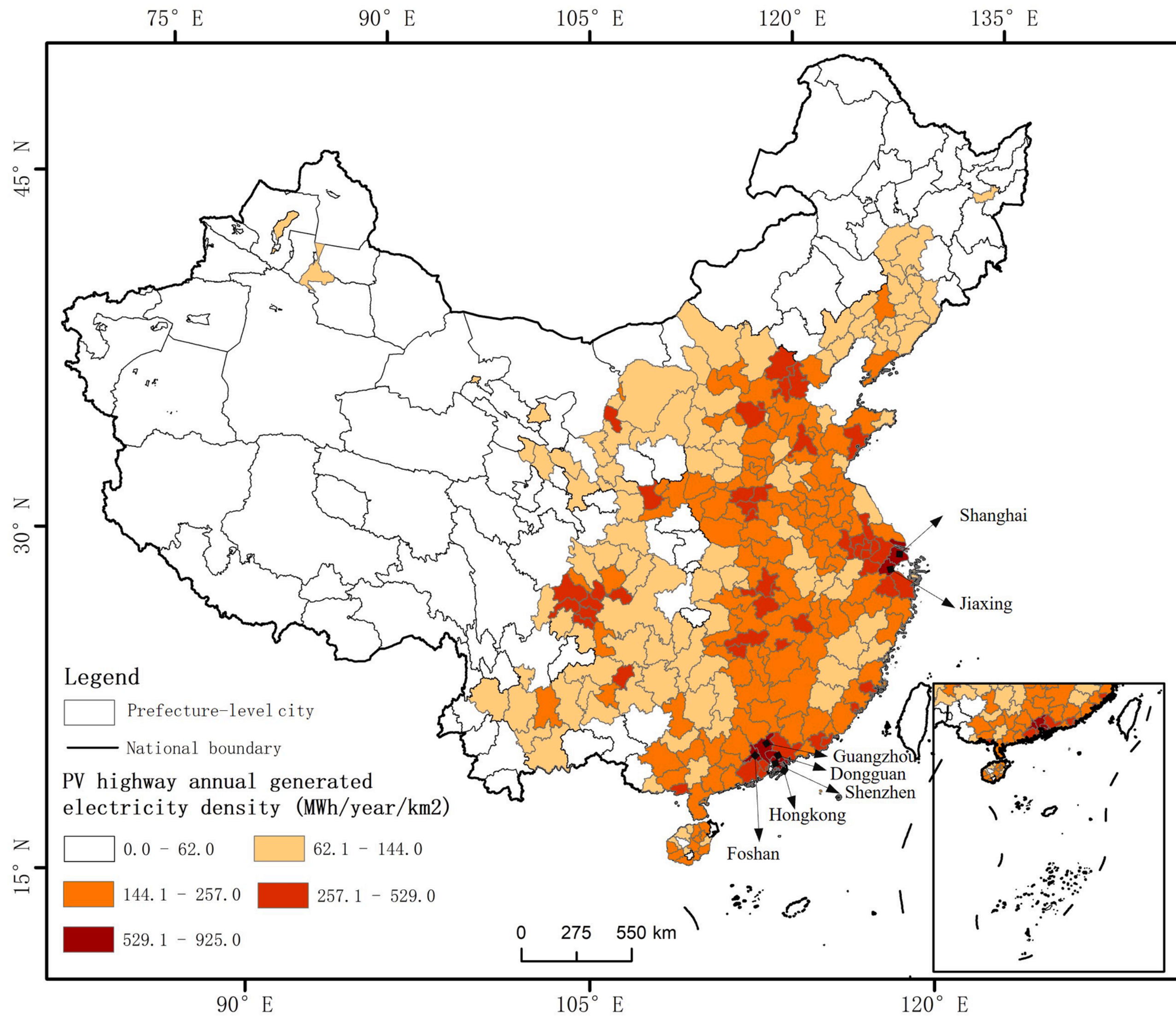

Fig. 12. The annual density of electricity generation of PV highways in China.

highway structures are questions that must be considered. In addition, the expense of installing PV panels on highways is extremely high, and the economic feasibility of PV highways has not been further explored [42]. Nevertheless, as PV technology evolves and the cost of PV systems continues to decrease, PV highways will become increasingly important for the development of smart transportation, EVs, and other businesses. Under the carbon peak and carbon neutrality targets, intelligent transportation and EVs have garnered much attention. As these systems become more prominent, they will provide feedback regarding the practical application of PV highway systems to establish more convenient and clean energy supplies. Our future work will focus on evaluating the economic and ecological benefits of PV highways and further explore the PV highway power distribution and consumption options at the regional scale.

5.2. Conclusion

PV highways are considered a promising application for decreasing greenhouse gas emissions, optimizing the energy structure, and accelerating the development of EVs and intelligent transportation in the context of peak carbon and carbon neutrality targets. In this study, a spatiotemporal model that considers the dynamic changes in shadow areas caused by the surrounding terrain on the highway surface is developed to quantify the solar PV potential of Chinese highways based on hourly irradiation data. The major results are as follows:1) highway mileage in China reached 143,684 km in 2020, with a total highway area of 3,957 km^2; 2) the total solar energy potential, installed capacity, and power generation of Chinese highways are 3,932 TWh, 700.85 GW, and 629.06 TWh, respectively; 3) the PV potential of highways is not significantly impacted by the shadows generated by the surrounding terrain; 4) the highest PV highway potential in China is in the southeast, followed by the northwest. Seven cities, including Shanghai, Guangzhou, and Foshan, have the highest potential for PV highway development.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

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