A Perspective on Solar Energy-powered Road and Rail Transportation in China

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***Abstract*—As essential pillars of passenger mobility and freight transport, road and rail transportation have experienced a rapid increase over the past years. This trend indicates an increase in energy consumption, especially electricity, due to higher energy efficiency and less carbon emission, but it exacerbates the contradiction between the power supply and demand. Nowadays, for additional power sources, increased solar power generation has been widely installed in their own available spaces for road and rail transportation, which has attracted a great deal of attention. This paper reviews the current status of solar power generation and its integrated application in the transport sector. Then, the photovoltaic generation potential of road and rail transportation in China are evaluated. Finally, further developments and perspectives of solar energy-powered road and rail transportation are presented, which not only contributes to lower-carbon and green transportation, but also promotes the development of renewable power generation for energy transformation. It is confirmed that solar energy-powered road and rail transportation is a promising approach for sustainable transportation with more renewable energy and less carbon emission.**

***Index Terms*—Potential evaluation, photovoltaic generation, road and rail transportation, solar energy.**

I. Introduction

GLOBAL energy demand has been continuously increasing as a critical foundation for economic growth and societies' development [1]–[5]. The International Energy Agency (IEA) reports that on a global basis, the transport sector accounts for 29% of finial energy use [6], [7], which has risen significantly in the past decades. The rapid increases in energy consumption are primarily driven by the demand in road and rail transportation. Among the various energies, oil dominates with a share of 94% in the end-use energy of the transport sector. Meanwhile, the transport sector is responsible for almost two-thirds of oil demand and nearly one-quarter of global carbon dioxide emissions from fuel combustion [8], [9]. It is a major contribution to air pollution and climate change. In 2015, the climate objective of the Paris Agreement was developed to restrict global temperature rise to 2.0°C. Following this objective, a profound energy transition is developing in many countries, where the reduction of the energy-related carbon emissions is the primary concern.

To achieve these global climate objectives, the deployment of renewable energy has been dramatically increasing due to its clean and pollution-free merits. In the last few years, renewable power generation is dominating the global market for new installed generation capacity [10], [11]. In 2019, the global capability of renewable power generation amounted to 2357 GW with a 176 GW increase. The wind and solar energy dominated at 623 GW and 586 GW, jointly accounting for 48% of the total. Among various types of renewable power generation, solar energy achieved the highest growth of 20% with a 98 GW installed capacity and dominated the capacity expansion of renewable power generation with a 55.7% share in 2019.

Electrification with renewable energy is emerging as a key solution for reducing carbon emissions in the transport sector. According to a report from the International Renewable Energy Agency (IRENA), renewable energy will make up two-thirds of the total energy consumption by 2050 [12]. Electricity has become the central energy carrier, which grew from a 20% share of the finial consumption to an almost 50% share. Meanwhile, it was reported that renewable electricity paired with deep electrification in the transport sector could reduce carbon emission by 60% in 2050. Due to rapid reductions in costs, this approach is getting cheaper than fossil fuel-based alternatives. It also lowers local air pollution with more positive socio-economic benefits.

The electrification in the transport sector is primarily driven by electric vehicles (EVs) in road transportation and electrified railways (ERs) in rail transportation. EVs have attracted extensive interest for reducing carbon emissions and alleviating fuel depletion, which is one of the best approaches to greatly reduce oil consumption in road transportation [13]–[20]. In the past few years, almost 3.5 million EVs have been sold in China and the China EV100 organization forecasts that sales will be dramatically increased to more than 80 million EVs by 2030. Due to the popularity of EVs, the consequent charging demand represents a significant load with increasing electricity consumption. A large-scale penetration of EVs may add more pressure on the utility grid. Except for charging stations, as with the increasing road networks, more electricity is consumed by service facilities alongside the roads, e.g., service areas on the highway, lighting and ventilation loads in tunnels. Thus, additional power supply with renewable energy is suggested as a feasible solution to offer more electricity for

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road transportation. ERs are one of the effective approaches in order to achieve carbon emission and decrease energy consumption in

rail transportation. From an energy and emission point of view, ERs with a strong reliance on electricity are one of the most energy-efficient, lowest-emitting and most-electrified transport modes [21]–[28] and it is one of the highest-consumption for end users in the utility grid. The IEA forecasts that the global rail network will expand from 1.6 to 2.1 million kilometers with a 34% increase between 2016 and 2050 [29]. This strong growth of rail transportation will increase rail electricity demand to nearly 700 TWh in 2050. This means that additional power sources need to be introduced into the rail sector. More renewable energy generation is suggested for installation in road and rail transportation, which is a profound approach for providing the addition power supply and reducing carbon emission in the transport sector.

Solar energy is one of the most widespread and important types of renewable resources. Solar energy can be collected by photovoltaic (PV) panels installed at power stations [30]–[32], in building walls [33]–[35], on rooftops [36]–[38], in parking lots [39]–[41] and etc. Due to flexible installations, PV generation has a greater potential for transport integration among the different types of renewable power generation. Road and rail transportation covers much of the settled land surfaces and can directly receive solar energy, which enables PV generation to be easily implemented on their own infrastructures and ancillary facilities in transport sectors. In addition, PV generation integrated into road and rail transportation can take full advantage of the existing buildings and available spaces to offer more renewable electricity without increasing land use.

This paper investigates the perspective of solar energy-powered road and rail transportation in China. Since there is abundant solar energy on the land and surfaces covered by road and rail transportation, solar energy-powered road and rail transportation is a promising pathway to displace fossil fuel, increase efficiency, and reduce carbon emission in the transport sectors. As with technology advances in the future, this approach with PV generation integrated into road and rail is getting cheaper than fossil fuel-based alternatives and also lowers air pollution with more positive socio-economic benefits. The remainder of this paper is organized as follows. Section II reviews the current status of solar generation and its integrated application in the transport sector over the past few years. In Section III, PV generation potential in road and rail transportation is evaluated in China. In Section IV, the future development and perspective of the solar energy-powered road and rail transportation are discussed. Finally, Section V provides conclusions.

II. Current Status

A. Distribution of Solar Energy

China has abundant solar energy resources due to its broad areas with rich solar radiation. The annual received solar energy is 1.7×10^{12} on the full land surface in China [42]–[44]. The annual surface absorption of solar resources is as much as 280 times the total coal reserves in China, which indicates that the huge solar resource is a promising alternative renewable energy for energy transformation.

According to the Solar Energy Resources Center of China Meteorological Administration, the average radiation in China is 1492.6 kWh/m^2 annually, with over 2000sunshine hours [45]–[47]. However, the received solar radiation is not evenly distributed and is greatly diverse across the entire country. The annual radiation ranges from less than 1000 kWh/m^2 in Sichuan basin to more than 1800 kWh/m^2 in the northwest region. As shown in Table I, the provinces located in different latitudes have different levels of solar radiation. Based on the acceptable amount of annual irradiation, China is divided into four available zones. The received solar energy in Zones I, II and III account for 96% of the total solar resource. These regions are primarily located in the north, the northwest and the northeast, with the annual solar radiation of more than 1050 kWh/m^2.

For road transportation, the highway is an important part with higher traffic density, and where the operating speed is between 80 km/h and 120 km/h. In China, the highway network is made up of 7 capital radials, 11 north-south vertical lines, 18 east-west horizontal lines, regional loop lines, and connecting lines. In recent years, China's highways have experienced rapid growth. The total mileage of highway networks in China increased from 84900 km in 2011 to 142593 km with an average annual growth of 7.7% [48]. The lengths of China's highways are 9248 km in Zone I, 44376 km in Zone II, 72289 km in Zone III, and 16680 km in Zone IV, respectively. As seen from Table I, the highway network in China is primarily located in the central and eastern regions with relatively abundant solar resources, accounting for a share of 81.8% of the total mileage. Meanwhile, these regions are the power load centers of China, which can provide a sufficient accommodation of renewable electricity.

TABLE I
Distribution of Solar Resources in China

Zone	Annual irradiation (kWh/m^2)	Region	Highway mileage (km)	Railway mileage (km)	
				Conventional	High-speed
I	Q >1750	Qinghai-Tibet Plateau, northern Gansu, northern Ningxia, southern Xinjiang, northwestern Hebei, northwestern Shanxi, southern Inner Mongolia, southern Ningxia, central Gansu, eastern Qinghai, southeastern Tibet and Hainan	9248	2239	544
II	1400 < Q <1750	Shandong, southeastern Hebei, southwestern Shanxi, northern Xinjiang, Yunnan, northern Shanxi, southeastern Gansu, southern Fujian, southern Guangdong, northern central Jiangsu, and northern Anhui	44376	35370	5504
III	1050 < Q <1400	Henan, Jilin, Liaoning, middle and lower reaches of the Yangtze River, Fujian, Zhejiang and Guangdong	72289	54695	19016
IV	Q <1050	Sichuan, Guizhou and Chongqing	16680	9696	3936

As for rail transportation, the conventional railway refers to the rails operating at a maximum speed under 200 km/h, while the high-speed railway covers the train journeys with a maximum speed above 250 km/h. According to [48], the total mileage of China's railway is 131000 km with 102000 km for conventional railways and 29000 km for high-speed railways at the end of 2018. It was estimated that the lengths of China's conventional railways are 2239 km in Zone I, 35370 km in Zone II, 54695 km in Zone III, and 9696 km in Zone IV, respectively. It was determined that the conventional railways are primarily located in Zones II and III, including the Beijing-Tianjin-Hebei region, the Yangtze River region, and central and southern China; and the mileage of conventional railways in China is relatively lesser in the northwest and southwest regions. The conventional railways in Zones II and III account for 68.7% of the total mileage. As for high-speed railways, it was reported that the total high-speed railway was over 30000 km, among which the railway operating 300 km/h exceeds 10000 km. In China, the development of eight verticals and eight horizontals of high-speed railways are planned with a larger high-speed railway network in 2030. It was calculated that the mileages of China's high-speed railways are 544 km in Zone I, 5504 km in Zone II, 19016 km in Zone III, and 3936 km in Zone IV, respectively. Similar to the conventional railways, high-speed railways are primarily in central and eastern China with a share of 84.5%. In these regions, the sunlight hours are more than 2200 hours with abundant solar energy.

Consequently, it was determined that the road and rail transportation can receive relatively abundant solar energy and have a huge generation potential of solar energy in their own available spaces, including the covered land, the slopes, the medians and the building rooftops in road and rail transportation. It further shifts energy transformation of the road and rail transportation to more renewable power generation and consumption.

B. Development of PV Generation

In recent years, the development of PV generation has been rapidly increasing, especially in China, whose new installed capacity of PV generation ranks first throughout the world. The continuous technological upgrading of enterprises and the optimization of the PV market are the important factors, which contribute to the global energy transformation for more renewable energy consumption. The technological innovation and advancement of the PV generation sector will continue to drive industrial upgrading, along with the production and quality of photovoltaic cells, which have continuously improved year by year. In particular, the rapid progress in the conversion efficiency of PV panels is being achieved. The conversion efficiency of monocrystalline silicon and polycrystalline silicon solar energy cells reached 17–19% and 15–17%, respectively. As with the technology advances, the costs of PV power generation have fallen sharply, which pushes forward the connection of PV generation at ordinary electricity prices sooner. Thus, more PV generation will be integrated into the power system with more renewable power supply.

It was reported that the new installed capacity of PV generation is 30.1 GW in 2019, which accounts for around one quarter of the total new installed generation in China. Compared to 2018, the increasing of the cumulative generating capacity is only 5.8%, while the PV generation has a higher growth of 17.6%, thereby resulting in more renewable power generation [49], [50]. The share of PV generation in the total generation has expanded from 43.2 GW in 2015 to 204.3 GW in 2019, with a 373% increase over the past five years. As with continuous development of PV generation, the share of PV generation in the cumulative generating capacity increased from 2.8% in 2015 to 10.2% in 2019, which was the fastest growth among different generation types. The PV produced electricity was as much as 224.3 TWh in 2019. However, as the accumulative installed capacity of PV generation is rapidly increasing, severe solar curtailment, which refers to the ratio of the abandoned solar energy in all the available solar energy, arose in the past several years, which is highlighted as a potential limiting factor to the long-term growth of PV generation. In 2015, the annual average solar curtailment rate exceeded 12%. Especially, in Northwest China, Gansu and Xinjiang, experienced the highest solar curtailment rates with 31% and 26% [51], respectively. For mitigating this challenge, several methods on renewable power accommodation were adopted in China [52]–[55], including the flexible generation, the power system interconnection and the demand side management.

TABLE II
DEVELOPMENT OF PV GENERATION IN CHINA

Year	Cumulative generating capacity (GW)	Total electricity production (TWh)	Installed capacity of PV generation (GW)	Electricity production of PV generation (TWh)	Solar curtailment (%)
2019	2010.7	7500.0	204.3	224.3	2.0%
2018	1899.7	7110.0	174.2	177.5	3.0%
2017	1777.1	6495.1	129.4	118.2	5.8%
2016	1650.5	6142.5	77.4	66.2	10.1%
2015	1525.3	5810.6	43.2	39.2	12.6%

Consequently, the rapid development of PV generation is associated with significant solar curtailment, which is a main obstacle for future development of PV generation. Since there are an abundance of received solar energy and increasing power demand in highway and railway networks, the integration of PV generation and road and rail transportation, with the implementation of the solar-energy powered transportation, is a promising approach of not only contributing to the sustainable and low-carbon development of the transport sector, but also promoting renewable power generation.

C. Existing Installations

Among variable renewable power generations, due to the flexible access by installing solar panels in the own available spaces of road and rail transportation, solar power generation is the most suitable and promising approach of providing a more renewable power supply [56]–[60]. Thus, many road and rail operators are taking full use of their own space to install solar panels and operate their own solar power generation.

With rail transportation, several examples of existing installations were found in China. In 2008, the first-ever rooftop PV generation on railway stations was installed at Beijing South railway station [61], [62]. In this demonstration project, the thin-film photovoltaic panels were employed for photovoltaic conversion. The installation covers around 14000 m^2 in the station rooftop with its maximum capacity being 220 kW due to relatively lower photovoltaic conversions. The annual produced electricity was estimated to be 223.6 MWh. In 2013, a 10.0 MW rooftop PV generation was installed at Hangzhou East railway station [63]. In this project, crystalline silicon solar panels with a rating of 230 W were installed. There are 23480 panels on the station building, 12900 panels on the south canopy, and 7300 panels on the north canopy, respectively. The total installation covers a total surface of around 79000 m^2. Due to the higher photovoltaic conversion of crystalline silicon solar panels, it produces about 10.4 GWh electricity annually. These PV generation installations on the station rooftops can not only supply their own electricity consumption, but also deliver the surplus electricity to the local grid. As for the available space in the railway depots, PV generation can also be installed [64]–[66], including the rooftop installation of 2.4 MW PV generation at Shaling depot in 2016, the rooftop installation of 1.0 MW PV generation at Xizhaotong depot in 2016 and the rooftop installation of 5.0 MW PV generation at Yuzhu depot in 2018, respectively.

Similar installations of PV generation can also be found in other countries. In Japan, East Japan Railway Company (JR-East) conducts many environmental conservation activities. Following the Paris Agreement, which is a new international framework for the global warming countermeasure after 2020, JR-East set its environmental goal, which aims at a 25% reduction of the total energy consumption of railway services in 2031 compared to that in 2014 [67]–[69]. Thus, JR-East has been promoting the introduction of self-consumption of renewable energy, particularly solar energy generation. In 2011, JR-East operated its first distributed 453 kW solar power generation above the entire platform for tracks 9 and 10 at Tokyo Station and the produced electricity serves the traction network of Tokaido Line trains. In 2014, another distributed 1050 kW solar power generation was installed inside Keiyo Rolling Stock Center. The generated electricity is used to reduce costs at the center and operate their own railways via the distribution lines.

In Belgian, 16000 solar panels, each with a rating of 245 W, are installed on the roof of a 3.6 km rail tunnel [70], [71]. This solar tunnel is the first of its kind throughout the world in that its railway infrastructures are being used to generate green electricity. The solar installation covers a total surface area of 50000 m^2 and supplies 3300 MWh of electricity annually. The produced electricity by the installed solar power generation has been used to not only power rail infrastructures, including lightings, signals, and stations, but also power the electric trains in the Belgian rail network. This solution of solar installation on the roofs of rail tunnels in Belgian is estimated to reduce carbon emission by 2400 tons per year.

In Australia, Byron Bay Railway Company launched an on-board solar energy-powered electric train [72], [73]. Special curved solar panels were fitted and installed on the train roofs. These solar panels can provide up to 6.5 kW of solar power to charge the on-board 77 kWh battery storage system for supplying traction motor, lighting, control circuits and air compressors. In addition, there is another large array of solar panels on the station rooftops capable of producing up to 30 kW, which is connected by the feeder lines in the traction network to power the operating trains.

As for road transportation, the most common solution is to integrate the solar energy generation in EV charging stations, which have been implemented in many regions [74]–[80]. With such cases, charging an EV using solar energy even further lowers its overall carbon emissions. In 2017, a PV generation-integrated EV charging station in Shanghai was conducted with 1002 solar panels installed, and it could produce around 500 kWh electricity per day. This EV charging station can provide charging service with over 400 EVs in one day. In 2017, another example of PV generation-integrated EV charging station was implemented in Xuguantun service area, Jingjintang Expressway [81]. In this implementation, the rating of PV generation is around 290 kW and there is an additional energy storage system with a rating of around 230 kWh. Similar installations are usually found in industrial parks. As an alternative means of making full use of the covered land, the use of solar pavements has attracted wide attention. In China, a 1080 m long solar energy-powered highway was built in the Jinan ring highway, which is the world's first solar energy-powered highway where heavy trucks operate [82]. The total cost of this solar energy powered highway in China was 41 million RMB, where a per-square-meter cost is around 7000 RMB. In Zhejiang, China, another solar energy powered road, named "super road", is in progress, which combines the solar energy generation, the energy storage, the mobile wireless charging and the capability for driverless vehicles.

Several other existing examples were carried out in foreign countries. In America, an EV autonomous renewable charger (ARC) was developed [83], [84], which is made up of a self-contained charging and energy-storage system powered by photovoltaic cells. In California, some charging stations are directly supplied by EV ARC and are not connected to the grid. Each of the charging stations has a 4.28 kW sun-tracking solar panel canopy, and 32 kWh energy-storage battery pack, which allows two EVs to charge simultaneously. Thus, EVs will be charged using 100% renewable energy. A solar energy powered road, named "Wattway," was constructed along a 1 km long country road in France at a cost of €5 million [85]. This solar energy-powered road covers 2,800 m^2 of solar panels with the protection of silicone layers, which can withstand nearly 2000 vehicles per day. In addition, in the same year, two demonstration bicycle roads using thin-membrane solar pavements, were constructed in Belgium and Holland.

These existing examples of solar installations in rail and road transportation have demonstrated the feasibility and availability of solar energy-powered road and rail transportation. It was also confirmed that the usage of solar energy potential in their own available spaces will play a vital role in the power supply for the transport sector. In addition, since the installed PV generation is in the demand side, local loads, with more consumption of renewable electricity, and a higher penetration of renewable energy will first use the produced electricity. Thus, this approach of taking full advantage of the solar energy potential in roads and rail transportation itself not only contributes to the energy transformation for more renewable power supply and less carbon emission, but also promotes the consumption of the generated renewable electricity by powering transport loads, including traffic infrastructures and ancillary facilities, electric vehicles, and electric trains.

III. Generation Potential of Road and Rail Transportation

A. Solar Energy Conversion

For clear statements of the entire solar energy-to-electricity conversion in PV generation, Fig. 1 shows the overall energy flow of solar energy conversion. The overall solar energy-to-electricity efficiency is made up of three parts: 1) the solar energy utilization that refers to the PV panel received solar energy in the total solar energy; 2) the photovoltaic conversion that describes the generated electricity from the received solar energy by solar panels; and 3) the power delivery that refers to the process of the electricity transformation via converters, lines, and transformers.

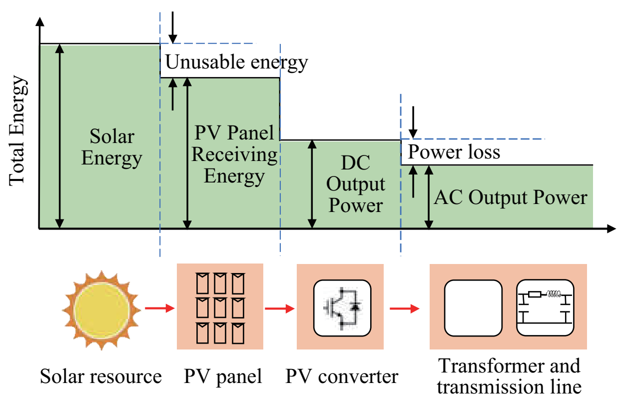


Fig. 1. Overall energy flow of PV generation.

For solar energy utilization, due to the low radiation intensity in the morning and evening, the start-up conditions of converters are not obtained. There is about 3% unavailable radiation in the morning and evening. Thus, the available solar energy is 97% of the received total. In addition, the dust on the surface of solar panels would also weaken the intensity of solar radiation on the panel surfaces and its output power would be decreased. As discussed in [86], the impact of dust on solar panels washed by rain is generally between 2% and 4%, while without being washed by rain, it increases to around 10%. Thus, a comprehensive consideration of the loss caused by the dust on the surface is taken as 6%, that is, the availability is taken as 94%. Consequently, considering the unavailable radiation in the morning and evening and the impacts of dust on solar panels, the solar energy utilization rate η_1 is obtained as:

$$\eta_1 = 97\% \times 94\% = 91\% \tag{1}$$

It is noted that the monocrystalline silicone is used as the main material of solar panels due to their high conversion efficiency, which occupies the vast majority of the PV market. The conversion efficiency of the dominated solar panels is between 17.5% and 20%. Since the photovoltaic conversion efficiency of solar panels produced by different manufacturers is different from each other, the average photovoltaic conversion of solar panels is conservatively set at 17.5% in the following analysis. Note that the photovoltaic conversion changes with different temperatures during operation. When the temperature of the solar panel rises higher than 25°C, its output current shows a downward trend with a temperature factor of −0.36%/°C. Thus, the availability of the temperature impact is generally set at 96%. Since there is practically a gap between the actual power and the nominal power, the actual photovoltaic conversions of different solar panels vary in a range of 3%. Thus, considering the temperature loss and the actual conversion differences, the average efficiency of photovoltaic conversion η_2 is obtained as:

$$\eta_2 = 17.5\% \times 96\% \times 97\% = 16\% \tag{2}$$

The power delivery efficiency is relevant to the converter efficiency, the plant efficiency and the available efficiency. In practice, the average efficiency of the grid-connected converter is 96%. Power loss in transmission lines and boost stations usually accounts for 5% of the total generated power, that is, the plant efficiency is initially set at 95%. Although the failure of photovoltaic cell is relatively low, the normal maintenance and the grid failures still cause additional power losses. In the following analysis, the availability of PV generation is assumed to be 99%. Thus, together with the converter efficiency, the plant efficiency and their availability, the efficiency of the power delivery η_3 is calculated as,

$$\eta_3 = 96\% \times 95\% \times 99\% = 90\% \tag{3}$$

As a result, considering the solar energy utilization, the photovoltaic conversion, and the power delivery, the average efficiency of the overall energy conversion η is obtained as,

$$\eta = \eta_1 \times \eta_2 \times \eta_3 = 91\% \times 16\% \times 90\% = 13\% \tag{4}$$

As seen, due to lower solar energy radiation in morning and evening and dust on solar panels, there is about 9% unusable solar energy of the total. Taking the actual photovoltaic conversion into account, the electricity produced by solar panels is only 16% of the received solar energy. In addition, since there are inevitable power losses in converters, lines, transformers and plants, the actual power injected into the utility grid is 90% of the electricity produced by solar panels. Consequently, taking all the aforementioned factors into account, the average efficiency of the overall solar energy conversion from the total solar radiation amount to the generated electricity into the utility grid is set at 13% in the following analysis.

B. Road Transportation

In this section, the generation potential of the highway in China is investigated as a study case. In the following analysis, the average annual solar radiation in different zones is initially set as 1750 kWh/m^2, 1575 kWh/m^2, 1225 kWh/m^2, and 1050 kWh/m^2 in Zones I, II, III and IV, respectively.

Since there is abundant space alongside highways, including the medians, the slopes and the covered land, it is convenient for PV installations. For simple analysis, it is assumed that there are two-way six lanes for the highways, where the width of each lane of the highway is 3.75 m [87]. Due to existing emergency lanes, the width of the highway pavement is 30 m wide. In addition, there are two slopes alongside highways, which is assumed to be 5 m wide on each side of the highways. Thus, for the covered land of the highways, their available own area of the highway in per kilometers is 40000 m^2. As discussed, the total mileage of the highway in China is 142593 km at the end of 2018, where the mileages are 9248 km in Zone I, 44376 km in Zone II, 72289 km in Zone III, and 16680 km in Zone IV, respectively. With the average efficiency of solar energy conversion at 13.0%, Table III presents the PV generation potential of the covered land of the highways. As seen, the total PV generation potential of the covered land of the highways is 999.2 TWh, which is much larger than the electricity consumption in road transportation. As seen, the PV generation potential of their own available space in Zone I is annually 84.2 TWh. Although this region has the highest solar radiation, there are relatively less highways in this region only with an 8.4% share of total potential. Since most highways are located in Zones II and III, the PV generation potential of these two regions are annually as high as 363.4 TWh and 460.5 TWh, respectively. The PV generation potential in Zones II and III accounts for 82.5%, which is dominate in the total generation potential. In addition, it plays a vital role in promoting the solar energy-powered road transportation. As for the PV generation potential in Zone IV, it is only 91.1 TWh per year due to the insufficient solar radiation, which accounts for 9.1% of the total potential.

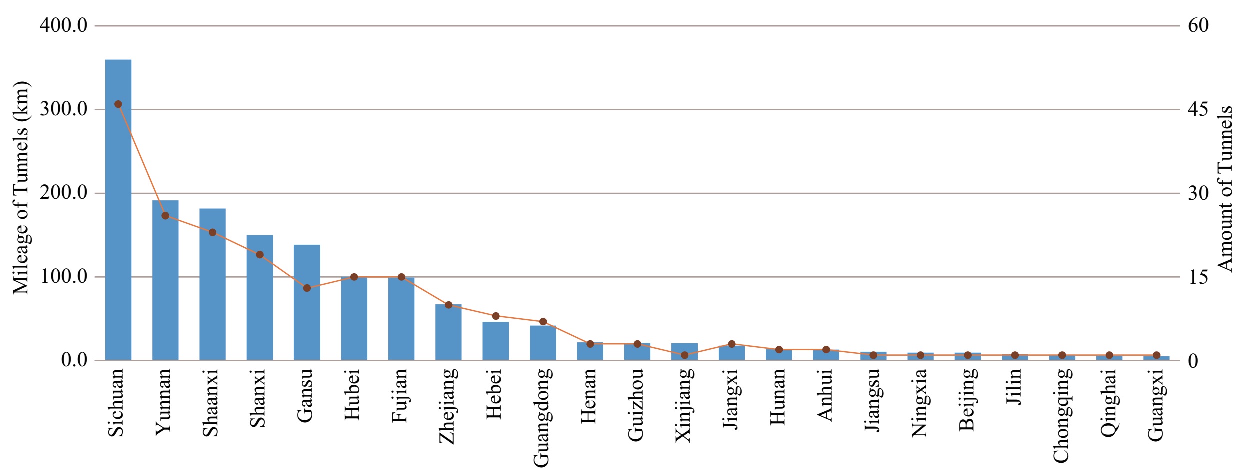
TABLE III
PV GENERATION POTENTIAL IN THE COVERED LAND OF HIGHWAYS

Zone	Mileage (km)	Area (km^2)	Generation potential (GWh)	Share (%)
I	9248	369.9	84.2	8.4%
II	44376	1775.0	363.4	36.4%
III	72289	2891.6	460.5	46.1%
IV	16680	667.2	91.1	9.1%

It was noted that the building rooftop in the highway service area can be used to install PV generation, which serves as an important supplement to its own electricity consumption. According to [88], service areas are arranged every 50 km on each side of the highways and the available space in the service areas is intended to be around 47000 m^2. Accordingly, it was calculated that there are around 2850 pairs of service areas in the highways and the amount of highway service areas is 185 in Zone I, 887 in Zone II, 1445 in Zone III, 333 in Zone IV, respectively. Consequently, the PV generation potential of the available service areas are annually 1978.1 GWh in Zone I, 8535.8 GWh in Zone II, 10815.5 GWh in Zone III, and 2136.4 GWh in Zone IV, respectively.

In the road tunnels, ventilation and lighting facilities are required, which is a main load in road transportation. It was noted that the medians on both ends of the tunnels can provide enough available space with the installation of PV panels. Meanwhile, the produced electricity can be locally consumed by the load of the tunnels, in particular the extra-long road tunnels. As shown in Fig. 2, there are 203 extra-long tunnels above 5000 meters in China. It was calculated that there are 14 extra-long tunnels in Zone I, 79 extra-long tunnels in Zone II, 60 extra-long tunnels in Zone III and 50 extra-long tunnels in Zone IV, respectively. As a study case, it is assumed that there are a total of 6000 m^2 areas to install PV panels on both ends of the tunnels. Based on the previous analysis, the PV generation potential of the available tunnel medians in the proximity of the extra-long tunnels is 19.1 GWh in Zone I, 90.1 GWh in Zone II, 57.3 GWh in Zone III, and 41.0 GWh in Zone IV, respectively. Compared to the generation potential of the covered land and the building rooftops, the PV generation potential of the tunnel medians in highways is relatively small due to their less available space at both ends of the tunnels for PV installations.

Table IV presents the PV generation potential of China's highways for different zones. As seen, the PV generation potentials of highways are annually 86.2 TWh in Zone I, 372.1 TWh in Zone II, 471.4 TWh in Zone III, and 93.3 TWh



Mileage	359.6	191.6	181.6	150.1	138.4	99.8	99.2	67.5	46.3	41.9	22.1	21.2	20.9	17.7	13.4	13.3	10.8	9.5	9.4	7.9	6.6	5.5	5.1
Amount	46	26	23	19	13	15	15	10	8	7	3	3	1	3	2	2	1	1	1	1	1	1	1

Fig. 2. Extra-long road tunnels above 5000 meters in China.

TABLE IV
PV GENERATION POTENTIAL OF CHINA'S HIGHWAYS

Zone	Covered land (GWh)	Building rooftops (GWh)	Tunnel medians (GWh)	Total potential (GWh)
I	84156.8	1978.1	19.1	86154.0
II	363439.4	8535.8	97.1	372072.3
III	460480.9	10815.5	57.3	471353.7
IV	91072.8	2136.4	41.0	93250.1
Total	999150.0	23465.8	214.4	1022830.2

in Zone IV, respectively. In addition, the corresponding PV generation potentials on the covered land, the building rooftops, and the tunnel medians for highways are annually 999.2 TWh, 23.4 TWh, and 214.4 GWh, respectively. It was calculated that the annual PV generation potential of highways is estimated to be 1022.8 TWh in total. Among the total potential, the PV generation potential of the covered land in road transportation dominated with a 97.7% share of the total.

Figure 3 shows the PV generation potential of the covered land, the building rooftops and the tunnel medians, respectively. As seen, the PV generation potentials in Zones I and IV, including the covered land, the building rooftops and the tunnel medians, account for only 8.4% and 9.1% of the total potential. The generation potential in Zones II and III dominate most of the generation due to more available space to install solar panels. The corresponding potentials in Zone II and Zone III account for 36.4% and 46.1% of the total potential, respectively.

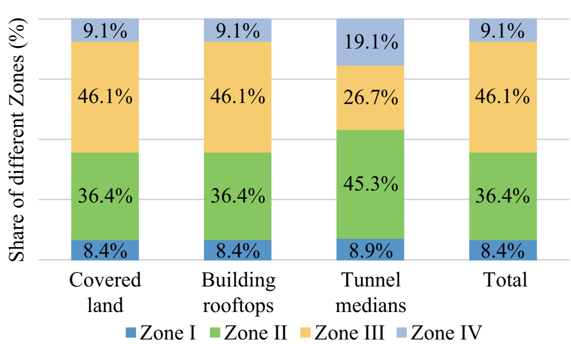


Fig. 3. Generation potential of the covered land, building rooftops and tunnel medians for highways.

C. Rail Transportation

As for rail transportation, since large spaces are normally available at the trackside land, the station rooftops and the train roofs, solar panels are inherently suitable for installation. Thus, this part presents the solar generation potentials of the trackside land, the station rooftops, and the train roofs for railways. Similar to the previous analysis, the average annual solar radiation is also set as 1750 kWh/m^2 in Zone I, 1575 kWh/m^2 in Zone II, 1225 kWh/m^2 in Zone III, and 1050 kWh/m^2 in Zone IV, respectively.

As for the covered land of rail transportation, according to [89], the standard width of the single-track railway is fixed at 8.6 m. Meanwhile, in practice, the slopes on both sides of railway are usually 1.0 m wide. As a result, per kilometer of railway, the covered land is 10600 m^2. Based on the previous analysis, by the end of 2018, the corresponding mileage of China's railways are 2783 km in Zone I, 40874 km in Zone II, 73711 km in Zone III, and 13632 km in Zone IV, respectively. Consequently, Table V shows the PV generation potential of the railway covered land. The corresponding generation potential of the railways covered land is annually 6.7 TWh in Zone I, 88.3 TWh in Zone II, 123.8 TWh in Zone III, and 14.4 TWh in Zone IV, respectively. Since there are relatively less railways in Zone I, the PV generation potential of this region only accounts for 2.8% of the total potential. The PV generation potential in Zones II and III dominate with a higher 37.0% and 52.0% share of the total potential. It is noted that the PV generation potential in these two regions accounts for 89.0% of the total, which is a key factor for the further development of solar energy-power railways. In addition, as for the PV generation potential in Zone IV, due to insufficient solar radiation in this region, it only accounts for 8.2% of the total potential.

TABLE V
PV GENERATION POTENTIAL OF TRACKSIDE LAND IN CHINA

Zone	Mileage (km)	Area (km^2)	Generation potential (GWh)	Share (%)
I	2783	29.4	6679.5	2.8%
II	40874	431.2	88292.4	37.0%
III	73711	777.7	123840.9	52.0%
IV	13632	143.8	19632.5	8.2%

For station rooftops, due to sufficiently available space and large electricity consumption of railway principal stations, it is convenient for rooftop installations and local utilization of PV generation in railway principal stations. Thus, the rooftops of railway principal stations are set as a study case in this part. Nowadays, China has a total of 71 railway principal stations, which are distributed with 19 in Zone II, 49 in Zone III, and 3 in Zone IV, respectively. In practice, the available areas in railway principal stations are usually in the range from 30000 to 100000 m^2. For simplified analysis, the average area of their own available rooftops in railway principal stations are set as 45000 m^2 for solar panel installations. Consequently, it is calculated that the PV generation potentials on the rooftops of railway principal stations are 175.1 GWh in Zone II, 351.1 GWh in Zone III, and 18.4 GWh in Zone IV, respectively.

As with the train roofs, there are a total of 72000 passenger carriages operating in China [90]. As required, the roof of each passenger carriage is 20.8 m long and 3.1 m wide. Due to the curvature of the train roofs, the availability of PV installations on train roof is assumed to be 80%. The utilization area of each passenger carriage is set as 50 m^2. Since the operating trains are closely relevant to the railway mileage in the corresponding regions, there is assumed to be 1529, 22465, 40513 and 7493 passenger carriages operating in Zones I, II, III and IV, respectively. Therefore, it is estimated that the PV generation potential on train roofs are annually 17.3 GWh in Zone I, 229.1 GWh in Zone II, 321.4 GWh in Zone III, and 50.9 GWh in Zone IV, respectively.

Table VI shows the PV generation potential of China's railways in different regions. Based on the previous analysis, it is determined that the PV generation potential of China's railway are annually 6.7 TWh in Zone I, 88.7 TWh in

TABLE VI
PV GENERATION POTENTIAL OF CHINA'S RAILWAY

Zone	Trackside land (GWh)	Station rooftops (GWh)	Train roofs (GWh)	Total (GWh)
I	6679.5	0.0	17.3	6696.8
II	88292.4	175.1	229.1	88696.6
III	123840.9	351.1	321.4	124513.4
IV	19632.5	18.4	50.9	19701.8
Total	238445.5	544.6	618.8	239608.9

Zone II, 124.5 TWh in Zone III, and 19.7 TWh in Zone IV, respectively. In addition, the corresponding generation potential on the trackside land, the station rooftops, and the train roofs in rails are annually 238.4 TWh, 544.6 GWh, and 618.8 GWh, respectively. As a total, the available electricity of PV generation installed in rail transportation is 239.6 TWh annually. Due to more available space in the covered land of railways, which is much larger than that on station rooftops and train roofs, its generation potential accounts for 99.5% of the total generation.

Figure 4 shows the PV generation potential of the trackside land, station rooftops and train roofs, respectively. As seen, the PV generation potential in Zones I and IV is relatively small with only 2.8% and 8.2% share of the total. Nevertheless, the PV generation potential in Zones II and III dominates, which accounts for 37.0% and 52.0% of the total, respectively. This is primarily because more space for PV installation is available in these regions in rail transportation.

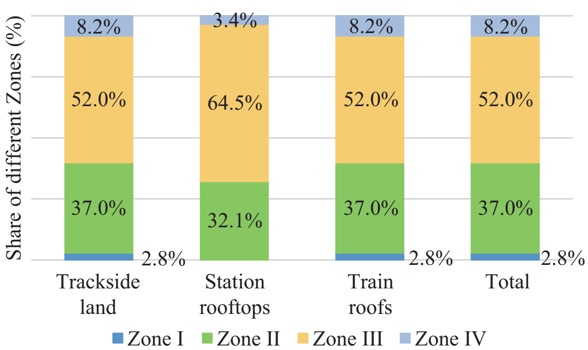


Fig. 4. Generation potential of trackside land, station rooftops and train roofs in China.

IV. PERSPECTIVE OF SOLAR ENERGY-POWERED TRANSPORTATION

A. Self-contained Energy Supply

As previously analyzed, since there is abundant solar energy in the available spaces of road and rail transportation, the solar energy-powered transportation is a promising approach of renewable power supply and carbon emission reduction, which will play a vital role in the sustainable development of the transport sector.

In the last decades, the total mileage of China's highways has been rapidly increasing. It is forecasted that the total mileage of highways in China will reach 249000 km in 2030 with an average annual growth of 5.7% during the last years. Compared to that in 2018, the total mileage of China's highways is predicted to have a 106400 km (74.6%) increase from 2018 to 2030. It is reported in [91], [92] that the average traffic flow of China's main highways will exceed 100000 vehicles per day in 2030, among which there will be 21000 EVs. It is assumed that the EVs charged on highways is 10% of the total. Assuming that an average electricity of 30 kWh is charged for each EV, the total charging load on highways reaches 57.3 TWh per year. Meanwhile, the existing infrastructures, including the lightings, the ventilations in the tunnel and the ancillary facilities alongside highways, consumes around 25.3 TWh electricity. As a result, it is found that the total electricity consumption of China's highway will be around 82.6 TWh annually by 2030.

As for rail transportation, China's railways, especially high-speed railways, has also experienced a rapid increase in recent years. By 2018, China's railway mileage was 131000 km with high-speed railways being 29000 km, which exceeds that of all other countries in the world. In [93], it was reported that by 2030, the development objectives of China's railways will increase the total railway mileage to 200000 km, where high-speed railways will represent over 45000 km with a share of 22.5%. As with the continuous development of railways, higher traffic density and higher operating speeds are achieved and the energy demand in rails is also dramatically increased. It is forecasted that the total energy demand will increase to 203.3 TWh annually. As part of the total, electricity consumption dominated the end-use energy of railways. The electricity consumption increased to 191.9 TWh, which accounts for 94.4% of the total.

Several approaches are proposed to take full advantage of the solar PV generation potential in road and rail transportation. In Fig. 5(a), solar pavements are installed on the covered land of the road transportation, where the produced electricity

(a) (b) (c) (d)

Fig. 5. Scenarios of solar energy-powered transportation. (a) Covered land. (b) Tunnel median. (c) Station rooftop. (d) Trackside land.

is delivered into the utility grid. In Fig. 5(b), solar panels are installed on the tunnel medians in road transportation, which can provide partial power demand for the ventilation and lighting facilities in road tunnels. As for rail transportation, there are sufficient spaces for solar installations at station rooftops and trackside land, as shown in Fig. 5(c) and (d). For solar panels installed at station rooftops, the produced electricity can offer its own consumption, while as with solar panels alongside railways, the produced electricity is fed into the railway traction network for powering locomotive loads.

Table VII presents the perspective of solar energy-powered road and rail transportation in 2030, respectively. It is reported in [94] that with more renewable power generation, the share of the renewable electricity in total increases to 24% in 2030. To clarify, the solar potential utilization (SPU) is used to describe the share of the produced solar power in the total potential, while the self-containing energy supply (SES) refers to the share of the renewable power produced by PV generation in transportation to satisfy its total demand. In addition, the renewable energy penetration (REP) represents the share of the renewable energy as part of the total energy consumption.

TABLE VII
FUTURE DEVELOPMENT OF SOLAR ENERGY-POWER TRANSPORTATION

Type	Demand (TWh)	SPU (%)	Generation (TWh)	SES (%)	REP (%)
Road	82.6	1%	10.2	12.4%	33.4%
		3%	30.7	37.2%	52.2%
		5%	51.1	61.9%	71.1%
Rail	191.9	5%	12.0	6.2%	28.7%
		10%	24.0	12.5%	33.5%
		15%	35.9	18.7%	38.2%

As for road transportation, it was determined that the annual electricity produced by PV generation in road transportation is 10.2 TWh with SPU being 1%. In this case, it is calculated that the SES is 12.4% and the REP is 33.4%. For SPU to be 3%, more renewable electricity over 30.7 TWh is annually generated with SES being 37.2%, and REP being 52.2%. For 5% SPU, the produced electricity increases to 51.1 TWh, where the SES and REP are 61.9% and 71.1%, respectively.

As with rail transportation, with 5% SPU, the produced electricity by the railway itself is 12.0 TWh. The SES and REP are predicted to be 6.2% and 28.7%. If SPU increases to 10%, more than 24.0 TWh of electricity is provided with a 12.5% SER and a 33.5% REP. For a higher SPU of 15%, the produced electricity in railways reaches 35.9 TWh. In this case, the SES and REP increase to 18.7% and 38.2%, respectively.

Consequently, it is concluded that solar energy will play an important future role in the power supply of the road and rail transportation. In addition, the solar energy-powered transportation contributes to the sustainable and collaborative development of both transport and energy sectors.

B. A Blueprint of Further Development

As discussed, in 2030, PV generation installed in road transportation will provide over 10 TWh electricity with the minimum SPU, which can supply over 10% electricity of the total energy consumption. As with rail transportation, similar installations of PV generation can produce around 12.0 TWh of electricity and it can represent at least 6% of the total energy consumption due to the larger energy consumption of railways. Since PV generation is installed in the demand side, the produced electricity first supplies the local loads, including traffic infrastructures and ancillary facilities, electric vehicles, and electric trains. The main grid supplied the remainder of the power demand. In the case where the produced electricity is more than the demand, the surplus power is delivered into the grid. Then, a higher penetration of renewable energy in the transport sector is achieved.

Therefore, the solar energy-powered transportation will serve not only as the basic conduit of transportation but also as the significant energy supply of transportation, and significant progress will be made in effectively solving the emerging problems of environmental pollution and the increasing energy consumption in both the transport and energy sectors.

From a sustainable point of view, severe challenges, including climate change and environmental pollution caused by existing emission and non-synergism featured developments, jeopardize the sustainable development of the energy and transport sectors. For the requirements posed by the sustainable development of both energy and transport sectors, green-development-oriented strategic planning, transformation and upgradation have already been essential approaches in both energy and transport sectors. In the global context of energy saving and emission reduction, the solar energy-powered road and rail transportation will play a vital role in the evolution of the sustainable transportation and energy transformation with greenhouse gas reduction and less pollution emission.

From a techno-economic point of view, both transport and energy sectors are the significant infrastructures and essential pillars of economic growth and social progress. This means that more PV generation is integrated into roads and railways, and the solar energy-powered transportation creates more emerging technologies and more business modes, which can greatly promote the technical progress and applications. In addition, this also introduces a batch of economic growth poles and then reshapes the development of relevant industrial clusters in both energy and transport sectors. Thus, solar energy-powered transportation greatly promotes the further evolution toward a low-carbon, green and sustainable future of both the energy and transport sectors, which brings about more positive benefits, including the technical progress, the industrial upgrading, and the economic growth.

The solar energy-powered transportation certainly boosts the wide spread of the low-carbon, green and sustainable development of energy and transport sectors and vigorously promotes the further evolution for energy transformation and sustainable transportation.

V. CONCLUSION

This paper presents the perspective of solar energy powered road and rail transportation in China. This approach achieves the collaborative transformation and upgrading of both energy and transport sectors. The road and rail transportation can receive abundant solar energy on the covered land and surfaces, where the annual PV generation potential is estimated to be 1022.8 TWh and 239.6 TWh in their own available space of road and rail transportation, respectively. Form the power supply and demand point of view, the further development of the solar energy-powered transportation in 2030 is explored, which achieves a green and clean transportation with more renewable energy supply and less pollution emission. Moreover, the solar energy-powered transportation is also found to be a promising approach for the sustainable and collaborative development of both energy and transport sectors. Finally, it is confirmed that the collaborative approach can not only contribute to the further evolution of a low-carbon, green and sustainable transportation but also greatly promote the renewable power accommodation for energy transformations.

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