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Roofing Highways With Solar Panels Substantially Reduces Carbon Emissions and Traffic Losses

Hou Jiang[1], Ning Lu[1], Jun Qin[1], Ling Yao[1], Xu Lian[2], Jijiang He[3], Tang Liu[4], and Chenghu Zhou[1]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [2]Department of Earth and Environmental Engineering, Columbia University, New York, NY, USA, [3]Research Center for Energy Transition and Social Development, Tsinghua University, Beijing, China, [4]School of Information Engineering, China University of Geosciences (Beijing), Beijing, China

Hou Jiang, Ning Lu, and Jun Qin contributed equally to this work.

Key Points:

- We estimate the potential for roofing highways with solar panels worldwide and the associated co-benefits
- Global highway photovoltaics (PV) could generate 17.58 PWh yr^{-1} of electricity, 56% of which is attainable at a cost below \$100 MWh^{-1}
- Highway PV could offset 28.78% of current CO_2 emissions, avoid 150,000 traffic deaths, and reduce the socio-economic burden by \$0.43 trillion

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

N. Lu and L. Yao,
lvn@lreis.ac.cn;
yaoling@lreis.ac.cn

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Author Contributions:

Conceptualization: Hou Jiang, Ning Lu, Jun Qin
Data curation: Ling Yao, Jijiang He, Tang Liu
Formal analysis: Hou Jiang, Xu Lian
Funding acquisition: Ling Yao
Investigation: Ling Yao
Methodology: Ning Lu, Jun Qin
Project administration: Ling Yao, Chenghu Zhou
Resources: Hou Jiang, Tang Liu, Chenghu Zhou
Software: Jun Qin, Ling Yao, Jijiang He

Abstract Photovoltaic (PV) installations are a leading technology for generating green electricity and reducing carbon emissions. Roofing highways with solar panels offers a new opportunity for PV development, but its potential of global deployment and associated socio-economic impacts have not been investigated. Here, we combine solar PV output modeling with the global highway distribution and levelized cost of electricity to estimate the potential and economic feasibility of deploying highway PV systems worldwide. We also quantify its co-benefits of reducing CO_2 equivalent emissions and traffic losses (road traffic deaths and socio-economic burdens). Our analysis reveals a potential for generating 17.58 PWh yr^{-1} of electricity, of which nearly 56% can be realized at a cost below US\$100 MWh^{-1}. Achieving the full highway PV potential could offset 28.78% (28.21%–29.1%) of the global total carbon emissions in 2018, prevent approximately 0.15 million road traffic deaths, and reduce US\$0.43 ± 0.16 trillion socio-economic burdens per year. Highway PV projects could bring a net return of about US\$14.42 ± 4.04 trillion over a 25-year lifetime. To exploit the full potential of highway PV, countries with various income levels must strengthen cooperation and balance the multiple socio-economic co-benefits.

Plain Language Summary Global efforts are underway to diversify environmentally sustainable strategies for photovoltaic (PV) installations to enhance the accessibility of green electricity. Here, we propose an innovative strategy to roof highways with PV panels and evaluate their electricity generation potential and social-economic co-benefits. Our analysis reveals that globally deploying highway PV systems across existing highway networks has the potential to generate 17,578 TWh of electricity annually, offsetting nearly 28% of concurrent global carbon emissions. Additionally, the highway PV could potentially prevent 150,000 traffic deaths annually and bring profits amounting to \$14.42 trillion over a 25-year lifetime. We emphasize that the highway PV may serve as a crucial nexus for promoting human, environmental, and economic sustainability.

1. Introduction

Replacing fossil fuels with renewable energy sources has become a critical priority on the global agenda (Davis Steven et al., 2018; Luderer et al., 2018). The United Nations Sustainable Development Goals (SDGs) set a target to substantially increase the share of renewable energy in the global energy mix by 2030 (Schmidt-Traub et al., 2017), and the latest Intergovernmental Panel on Climate Change (IPCC) report highlights the need for urgent actions to halve carbon emissions by 2030 (IPCC, 2022). In the past decade, the installed capacity of renewable energy has grown from 1.4 TW in 2012 to 3.1 TW in 2021 (IRENA, 2022). Solar photovoltaics (PV) contributes to more than 40% of this increment and is poised to steadily power a sustainable future (Victoria et al., 2021).

Such progress is encouraging, but enormous and more effective efforts are still urgently required to stay on track to meet the 1.5°C climate target and to tackle various emerging challenges (Welsby et al., 2021). Therefore, countries continue to explore strategies that not only reduce carbon emissions by expanding renewable energy deployment but also circumvent intractable problems (Hernandez Rebecca et al., 2015; Rabaia et al., 2021), such as the limited land available for PV installation in human settlements where the energy demand is usually high. The implementation of PV systems on highways (Figure 1), that is, roofing highways with PV panels, holds great promise to increase renewable energy production and to alleviate the contradiction between land availability and energy accessibility through the three-dimensional space use of land.

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Supervision: Ling Yao, Chenghu Zhou
Validation: Ning Lu, Xu Lian, Jijiang He
Visualization: Hou Jiang
Writing – original draft: Hou Jiang, Ning Lu, Jun Qin
Writing – review & editing: Hou Jiang, Ning Lu, Jun Qin, Ling Yao, Xu Lian

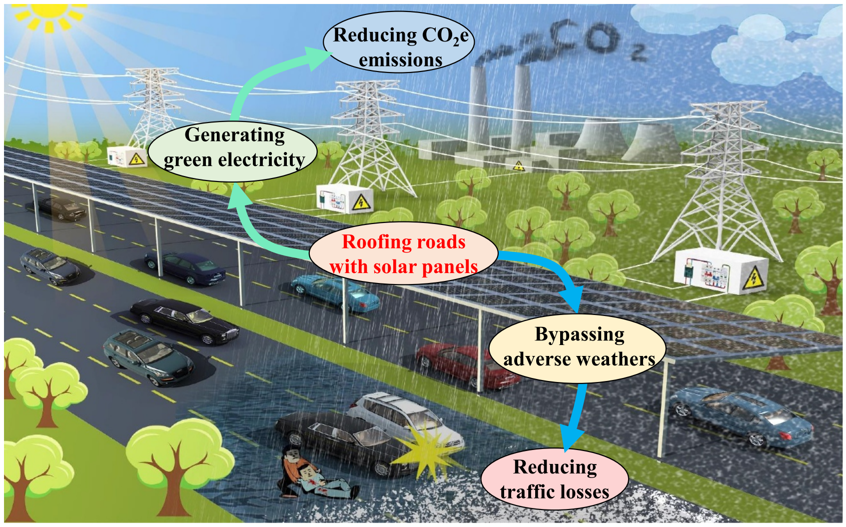

Figure 1. Schematic diagram of the highway photovoltaics (PV) system. Roofing highways with solar panels generates green electricity that is delivered to the grid to replace the electricity from fossil fuels, thereby contributing to CO_2e emission reductions. This PV system also protects cars on the highway from adverse weathers, thus reducing traffic losses (road traffic deaths and socio-economic burdens). For road lighting, PV panels are spliced together with transparent materials filling their gaps, and no structures are installed between uprights on both sides of highways.

Several pilot projects of highway PV in China, the United States (US), Germany, Austria, and Switzerland have already demonstrated the technical feasibility of using PV to supply electricity for highway rest areas and tunnels (Enkhardt, 2020; Steven, 2016). These projects imply that the benefits of the highway PV mainly embody two aspects. First, highway PV can reduce carbon dioxide equivalent (CO_2e) emissions by generating green electricity that can be delivered to the grid, thereby replacing electricity that would otherwise be generated by fossil fuel sources. The global highway network spans over 3.2 million kilometers on the Earth (Meijer et al., 2018). If the space above highways is entirely devoted to PV installations, considerable amounts of green electricity can be generated to offset carbon emissions, contributing to a net zero emissions future. Meanwhile, the use of already-developed highway surfaces is beneficial because this would not increase watersheds' imperviousness and reduce previous lands' disturbance.

Second, the unique advantage of highway PV over other ground-based PVs lies in the enormous reduction of road traffic losses. As the eighth leading cause of death worldwide (Foreman et al., 2018), road traffic accidents claim approximately 1.35 million lives and cause 50 million injuries each year (WHO, 2018). The social-economic burdens associated with these accidents are estimated to be about 2.7% of gross domestic product (GDP) in high-income countries and 2.2% of GDP in low- and middle-income countries (Wijnen & Stipdonk, 2016). The highway PV can protect cars from adverse weather conditions (e.g., rainy, snowy, and freezing), thereby reducing the incidence of road traffic accidents and the ensuing deaths and socio-economic burdens.

However, the two co-benefits of highway PV above have not been widely recognized, leading to underdeveloped highway PV. As a result, its role in accelerating energy transition and achieving SDGs has not yet been played. Here, we evaluate the potential and economic feasibility of this PV system worldwide by modeling the electricity generation per length of the highway and calculating the levelized cost of electricity (LCOE). We then quantify the CO_2e emission reductions based on country-level grid emission factors and estimate the reduced traffic losses via a probabilistic decomposition model that simulates the impact of both road weather conditions and driving speed on the traffic accident risks. Our comprehensive analysis reveals that huge returns can be attained if the highway PV systems are globally implemented and highlights that highway PV deserves attention in formulating global plans to support SDGs.

2. Materials and Methods

2.1. Assessing Electricity Generation Potential

The global highway distribution is acquired from the Global Roads Inventory Project (GRIP) database (Meijer et al., 2018), which provides lengths of freeways, primary roads, secondary roads, tertiary roads, and local roads at a spatial resolution of 5′ × 5′ for 222 countries (Figure S1 in Supporting Information S1). The data were strictly examined for quality in terms of spatial coverage, position error, completeness of attribute information, scale, data aging, etc. We decompose the road length of the central pixel along the north-south (N-S), east-west (E-W), northwest-southeast (NW-SE), and northeast-south (NE-SW) directions according to the road lengths in eight neighboring pixels (Figure S2 in Supporting Information S1). In this study, we focus on roofing freeways and primary roads with solar panels (collectively termed "highway PV" unless otherwise specified) while also evaluating the potential increment of extending this concept to secondary roads. Freeways refer to major national or regional roadways designed for high-speed vehicular traffic without direct access from properties or minor roads; primary roads are major arteries that carry large volumes of traffic within or between areas; and secondary roads are lesser arteries connecting smaller towns with lower traffic density than primary roads. For detailed characteristics of these road types, please refer to Table S1 in Supporting Information S1. It is noted that roofing solar panels in highway tunnels is impractical, but we are unable to filter out the tunnels due to the lack of road attributes. Given that the proportion of the road tunnel length is less than 1% on a global scale (Table S2 in Supporting Information S1), the uncertainty caused by the tunnels will not conclusively alter our estimates.

The highway PV is illustrated in Figure 1. We consider the installation of polysilicon PV modules with a peak power of 250 W. The length and width of the module are 1.650 m and 0.992 m, respectively. The long side of the PV module is designed to be oriented along the centerline of the highway. We assume that the road width meets the general road design standards that we glean from the reports issued by the United Nations Economic and Social Commission for Asia and the Pacific, the American Association of State Highway and Transportation Officials, the World Road Association and other online sources (Table S1 in Supporting Information S1). Under this assumption, the capacity density of PV installation is 4.84, 3.93, and 2.12 kW m^{-1} for freeways, primary roads, and secondary roads, respectively. For road lighting, PV panels are spliced together with transparent materials filling their gaps, and no structures are installed between uprights on both sides of highways. Besides, PV panels are fixed at a ten-degree tilt angle (Jacobson & Jadhav, 2018) toward the outside of the highways, allowing precipitation to naturally clean the solar panels (Li et al., 2020). PV roofs are 5.5 m above the highways. Several pilot projects in China, the US, Germany, Austria, and Switzerland have already demonstrated the technical feasibility of such highway PV installation (Enkhardt, 2020; Steven, 2016).

The open-source Global Solar Energy Estimator (GSEE) (Pfenninger & Staffell, 2016) is used to model highway PV electricity generation. GSEE takes hourly direct ($R_{\mathrm{dir},h}$) and diffuse ($R_{\mathrm{dif},h}$) horizontal solar radiation and ambient temperature (T_{a}) as inputs. Direct ($R_{\mathrm{dir},p}$) and diffuse ($R_{\mathrm{dif},p}$) irradiance on solar panels are calculated depending on PV installation geometry and sun position as:

$$R_{\mathrm{dir},p} = \frac{R_{\mathrm{dir},h} \cdot \cos(\alpha)}{\cos(90° - \theta_A)} \tag{1}$$

$$R_{\mathrm{dif},p} = R_{\mathrm{dif},h}\frac{1 + \cos(\alpha_t)}{2} + \rho \cdot (R_{\mathrm{dir},h} + R_{\mathrm{dif},h}) \cdot \frac{1 - \cos(\alpha_t)}{2} \tag{2}$$

$$\alpha = \cos^{-1}\left[\cos(\theta_z)\cos(\alpha_t) + \sin(\theta_A)\sin(\alpha_t)\cos(\theta_A - \alpha_A)\right] \tag{3}$$

where α denotes the angle between the sun's rays and solar panels, θ_A the solar azimuth angle, θ_z the solar zenith angle, α_t the PV tilt angle, α_A the PV azimuth angle, and ρ the surface albedo (default value 0.3). The irradiance on panels is further reduced by shading, soiling, and multiple reflection effects (a constant loss of 2% is assumed). The PV module temperature (T_{m}) varies with T_{a} and incident irradiance (G, the sum of $R_{\mathrm{dir},p}$ and $R_{\mathrm{dif},p}$) as:

$$T_{\mathrm{m}} = T_{\mathrm{a}} + c_T G \tag{4}$$

in which c_T is the temperature sensitivity parameter to solar radiation (0.035°C W^{-1} m^2 is suggested by Huld et al. (2010)). We assume a 10% loss in the conversion from direct current to alternating current, according to the experiments across 1,029 sites in Europe (Pfenninger & Staffell, 2016). The installed capacity is set to 1 kW, which makes the output equal to the CF, defined as the ratio of a PV module's actual output (kWh) to its maximum output under a standard test condition (kWp) over a specific period. The hourly solar radiation ($R_{\text{dir},h}$ and $R_{\text{dif},h}$) and temperature (T_a) are taken from the ERA5 data set (Hersbach et al., 2020), which has been used widely in a variety of areas and proven to be of high accuracy. For each grid box, we simulate the CF of solar panels with eight different azimuth angles ($\alpha_A \in \{0°, 45°, \ldots, 315°\}$, Figure S3 in Supporting Information S1). The electricity generation potential of a grid box is calculated as:

$$E = \sum_{i=1}^{8} \frac{D \times L_d}{2} \times CF_{\alpha_A} \tag{5}$$

where E denotes the electricity generation, D the installed capacity per unit length, and L_d the highway length in direction d. There are eight combinations for d and α_A, that is, (N-S, 90°), (N-S, 270°), (E-W, 0°), (E-W, 180°), (NW-SE, 45°), (NW-SE, 225°), (NE-SW, 135°), and (NE-SW, 315°). The simulation is conducted from 2015 to 2021. In addition to solar panels tilted at a ten-degree angle, we further model the PV outputs at a horizontally fixed angle (i.e., $\alpha_t = 0$) and at an optimal latitude-dependent tilt angle (Jacobson & Jadhav, 2018) to investigate the impact of PV tilt angles on the electricity generation.

2.2. Calculating Levelized Cost of Electricity

We use the levelized cost of electricity (LCOE) to analyze the economic feasibility of the highway PV projects (Bódis et al., 2019; IRENA, 2021). The formula for LCOE is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6}$$

where I_t represents the capital expenditures in year t, M_t the operation and maintenance (O&M) expenditures, F_t the fuel expenditures (zero for renewable energy projects), E_t the electricity generation, r the discount rate and n the lifetime of the PV system (25 years in this study). The LCOE value is the price of electricity required for a project where revenues equal costs. We assume all highway PV modules are installed in the first year of the lifetime at 2020 costs.

We use the statistical data of 16 countries provided by the International Renewable Energy Agency (IRENA, 2021) for the capital expenditures (including solar module costs, inverter costs, racking and mounting costs, grid connection costs, etc.) and compute the continent-level means as the values for other countries within the same continent (Table S3 in Supporting Information S1). Referring to the IRENA report (IRENA, 2021), we assume a constant O&M expenditure of US$17.8 per kW per year in the Organization for Economic Co-operation and Development (OECD) member countries, while US$9.0 per kW per year in non-OECD countries. The discount rate is used to discount future cash flows back to their present value, reflecting the risk and time value of money associated with the cash flows. The weighted average cost of capital (WACC) represents the average rate of return that a company expects to pay security holders to finance its assets and is calculated by weighing the cost of each capital component (equity, debt, etc.) in proportion to their respective share in the company's capital structure. WACC can be used as a discount rate for evaluating projects and investments (Bódis et al., 2019; Talavera et al., 2017) because it reflects the required return that investors expect to receive from the company and takes into account risk and the proportion of debt and equity used to finance the project. Our calculation assumes a WACC value of 5% for the OECD countries and China, where borrowing costs are relatively low and stable regulatory and economic policies tend to reduce the perceived risk of renewable energy projects, and a WACC value of 7.5% for the other countries (IRENA, 2021). Notably, the capital expenditures provided by IRENA are based on their Renewable Cost Database (IRENA, 2021), which only contains existing utility-scale residential and commercial (mostly ground-based) PV projects worldwide. Consequently, the calculated LCOE values do not entirely reflect the fact that the highway PVs should spend more on the support structures than the ground-based PVs. The worldwide costs of the support structures for the highway PV are unavailable because they have not been extensively implemented. However, we find that the cost of the support structures for the highway PV is approximately four times higher than that for the ground-based PVs, according to some planned PV projects in China (Table S4 in Supporting Information S1). It is reasonable to assume that this proportionality holds for each country because the increase in the cost of the support structures for the highway PV is mainly caused by the rising quantity of construction materials.

2.3. Quantifying CO_2e Emission Reductions

By assuming that the electricity generated by the highway PV is delivered to the grid to replace the electricity from other sources, we can estimate the CO_2e emission reductions that are considered as one of the co-benefits of highway PV. We calculate CO_2e emission reductions (C_r) based on the approach (IPCC, 2006) provided by IPCC:

$$C_r = (1 - R_c) \times AD \times \frac{EF}{(1 - R_p)} \tag{7}$$

where AD (activity data) is the amount of electricity consumption that equals the electricity generation of the highway PV in this study; EF (emission factor of the grid) refers to the CO_2e emission factor (tCO_2e MWh^{-1}) that is associated with each unit of electricity supplied by a grid; and R_c and R_p are the PV correction factors for AD and EF, respectively. R_c denotes the PV curtailment rate (%) that characterizes the grid's ability to absorb intermittent PV electricity, and $(1 - R_c)$ represents the proportion of highway PV generation delivered to the grid. R_p denotes the PV penetration rate (%), defined as the percentage of electricity generated from solar facilities. The grid emission factor has already considered all types of electricity generation in the grid, including zero-emission PV electricity, but the electricity from the highway PV will not replace other PV electricity in the grid. Consequently, the emission reductions calculated directly based on the grid emission factor are underestimated. Here, we use R_p to correct this underestimation as $\frac{EF}{(1 - R_p)}$.

Some countries have published their grid emission factors, such as the ones published by the Ministry of Ecology and Environment of the People's Republic of China, the Environmental Protection Agency of the United States, and the Department of Energy and Climate Change of the United Kingdom. Recently, the Institute for Global Environmental Strategies compiled a list of grid emission factors for 90 countries based on the registered Clean Development Mechanism (CDM) projects from the United Nations Framework Convention on Climate Change and the official CDM standardized baseline (IGES, 2021). We further complement the grid emission factors from some official government documents, the inventory of the Association of Issuing Bodies, the Climate Transparency Report, and Brander et al.'s technical paper (Brander et al., 2011). The extended list contains the grid emission factors for 156 countries/regions (Figure S4a and Table S5 in Supporting Information S1). We obtain the R_c only for eight countries (i.e., Australia, Chile, China, Germany, India, Japan, and the US), and China's seven sub-grids (i.e., North Grid, Northeast Grid, Northwest Grid, Central Grid, East Grid, South Grid, and Tibetan Grid). We find that the R_c is linearly correlated with the R_p at the 95% confidence level based on data in China's seven sub-grids (blue dots in Figure S5 in Supporting Information S1). The validation against the R_c values in the eight countries (green circles in Figure S5 in Supporting Information S1) proves the reliability of this linear relationship. Therefore, we estimate R_c for all countries without such factors (Figure S4b in Supporting Information S1) based on the linear relationship and the country-level R_p values (Figure S4c in Supporting Information S1).

We calculate the emission offset rate (R_o) to identify the contribution of the highway PV to carbon neutrality, which is expressed as the ratio of emission reductions (C_r) by the highway PV to anthropogenic emissions (C_a):

$$R_o = \frac{C_r}{C_a}. \tag{8}$$

Here, C_a refers to the total CO_2e emissions excluding land-use change and forestry (Figure S6a in Supporting Information S1) or the independent CO_2e emissions from the transportation sector (Figure S6b in Supporting Information S1) in 2018 (Climate Watch, 2022). $R_o \geq 1.0$ indicates that carbon neutrality is ultimately achieved for the whole country (or transportation sector) through highway PV. If $R_o < 1.0$, the larger value represents a state closer to carbon neutrality. The emissions data in 2018 are collected from the Climate Analysis Indicators

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Tool (CAIT) developed by the World Resources Institute, which provides a comprehensive and comparable database of CO_2e emissions for multiple sectors in individual countries worldwide.

2.4. Estimating Reduced Traffic Losses

We estimate the reduced losses by assuming that the traffic accident risks on highways induced by adverse weather conditions are avoided after highway PV installations. We first estimate country-level losses and then establish a probabilistic model to decompose country-level values to the grid-box-level ones based on the road distribution weighted by the traffic accident risks. The model considers the impact of road weather conditions and driving speeds on the risks since the former leads to spatial divergences while the latter determines the variability among road types. The probabilistic decomposition model is formally expressed as:

$$L_{i,j,k} = L_0 * \frac{A_i^{(w)}}{A_0^{(w)}} * \frac{P_{i,j} W_j}{\sum_{j=1}^{4} P_{i,j} W_j} * \frac{A_{i,k} R_k}{\sum_{k=1}^{5} A_{i,k} R_k} \tag{9}$$

$$A_0^{(w)} = \sum_{i=1}^{N} A_i^{(w)} \tag{10}$$

$$A_i^{(w)} = \sum_{j=1}^{4} \left\{ P_{i,j} W_j \sum_{k=1}^{5} A_{i,k} R_k \right\} = \sum_{j=1}^{4} P_{i,j} W_j \sum_{k=1}^{5} A_{i,k} R_k \tag{11}$$

where $L_{i,j,k}$ denotes the traffic loss of the ith grid-box caused by the jth weather on the kth road with $i \in \{1,2,\cdots,N\}$, $j \in \{1$: No precipitation, 2: Rain, 3: Sleet, 4: Snow$\}$, and $k \in \{1$: Freeways, 2: Primary roads, 3: Secondary roads, 4: Tertiary roads, 5: Local roads$\}$, L_0 the country-level loss, N the number of gird-boxes within a country, $P_{i,j}$ the probability of the jth weather in the ith grid-boxes, W_j the traffic accident risk caused by the jth weather, $A_{i,k}$ the length of the kth road in the ith grid-boxes, and R_k the traffic accident risk on the kth road.

The benefits from the highway PV are the reduced losses on freeways and primary roads under rainy, sleet, and snowy weather (i.e., $j = 2, 3, 4$ and $k = 1, 2$). In fact, many human factors, such as driving under the influence of alcohol and other psychoactive substances, nonuse of motorcycle helmets, seat belts, and child restraints, as well as distracted driving, also increase the traffic accident risk. The impact of these factors keeps consistent across all weather conditions and road types, and therefore is not simulated in this study. Here, we estimate the reduced losses in terms of road traffic deaths and socio-economic burdens associated with traffic accidents. The socio-economic burdens further include economic burdens arising from the dynamic changes in the population, savings behavior, accumulation capital, etc. (Chen et al., 2019), and social burdens in terms of medical treatment, production loss, human costs, property damage, and administrative costs (Wijnen & Stipdonk, 2016). The number of road traffic deaths for each country (Figure S7a in Supporting Information S1) is taken from the World Health Organization (WHO) report (WHO, 2018). The 2020 GDP data (Figure S7b in Supporting Information S1) comes from the World Bank statistics. The traffic-related economic burden as a percentage of GDP for individual countries (Figure S7c in Supporting Information S1) is derived from the study of Chen et al. (2019). For globally estimating the traffic-related social burden, we extract the records from relevant reviews (Bougna et al., 2022; Wijnen & Stipdonk, 2016) and find that the percentage of the social burden in GDP (Wijnen et al., 2009) is linearly correlated with the percentage of the economic burden in GDP at the 95% confidence level (Figure S8 in Supporting Information S1). Based on the linear relationship and the economic burden from Chen et al. (2019), we estimate the percentage of the social burden in GDP for each country without records (Figure S7d in Supporting Information S1). The summed global social burden is US$2.5 ± 0.9 trillion, or 2.9% ± 1.1% of the 2020 GDP (US$84.54 trillion), which is close to the generally accepted estimate of 3% (WHO, 2021).

Malin et al. (2019) analyzed the effects of weather on traffic accident risks from the driver's view by fusing hourly meteorological, accident, and traffic data. Those values from Malin et al. (2019) (Table S6 in Supporting Information S1) are adopted in our probabilistic decomposition model (Equation 9). The spatial distribution of the probability of different precipitation types (Figure S9 in Supporting Information S1) is calculated using hourly ERA5 reanalysis data during 2015–2021. Logistic regression has been widely used in the literature for the risk-speed relationship (Hussain et al., 2019), and it is presented as various S-shaped curves (Figure S10 in Supporting Information S1). Hussain et al. (2019) systematically investigated 1,479 relevant articles or reports and chose 15 studies that provide sufficient information on the accident risk–speed relationship (blue curves in Figure S10 in

Supporting Information S1). In this study, the multivariate meta-regression result (red curve in Figure S10 in Supporting Information S1) based on these 15 studies is used to determine the traffic accident risk for different road types. The expression of the S-shaped curve is:

$$R = \frac{1}{1 + e^{5.9829 - 0.1023 * v}} \tag{12}$$

where R denotes the traffic accident risk and v the driving speed. Here, we use the average speed limits as the value of v to calculate the relative risks for different road types (Table S7 in Supporting Information S1).

2.5. Analyzing Investment and Return

We evaluate the net profit (NP) of investing in the highway PV over a 25-year lifetime:

$$NP = S + L - I \tag{13}$$

where S represents the electricity sales revenue being equal to the current electricity price multiplied by the electricity generation; L the reduced traffic losses in terms of socio-economic burdens; and I the total investment being equal to LCOE multiplied by installed highway PV capacity. The current electricity prices are obtained from the GlobalPetrolPrices.com website. These prices are collated and cross-checked manually based on multiple data sources and include all items in the electricity bill, such as distribution and energy costs, and various environmental and fuel cost charges/taxes. We note that CO_2e emission reductions also bring returns because the social costs of carbon are avoided. However, there are significant uncertainties in quantifying the social costs of carbon (Wagner, 2021). Thus, we only estimate such returns of the highway PV on a global scale based on the study of Rode et al. (2021), which found that CO_2 emissions are most likely to generate a social cost of US$2 ± 1 per t$CO_2$. In addition, we compare the capital expenditures (I_t in Equation 6) with the 2020 GDP to analyze the economic pressure imposed on the different World Bank income country groups (i.e., low-income, lower-middle-income, upper-middle-income, and high-income countries) when developing the highway PV.

3. Results

3.1. Global Potential and Costs

Our assessment shows that globally roofing highways with solar panels can generate 17,578 TWh per year, corresponding to an installed capacity of 13,087 GW if panels are installed at a ten-degree tilt angle. The potential is concentrated in or around densely populated and highly developed areas, such as eastern China, Western Europe, and the eastern US (Figure 2a). China (3,650 TWh yr^{-1}), European Union (EU) countries (2,087 TWh yr^{-1}), and US (2,000 TWh yr^{-1}) account for 44% of the global potential (Figure 2b), due to their vast territory and well-developed highway networks. The global spatial pattern of electricity generation reflects the combined effect of the highway distribution (Figure S1a in Supporting Information S1) and the solar resources (measured by CF, Figure S3 in Supporting Information S1). Spatially variable CFs lead to apparent differences in the electricity generation between countries owning similar installed capacities, for example, Canada versus Brazil and Russia versus Thailand (Figure 2b, Figures S3a, and S11a in Supporting Information S1). We further examine the impact of the tilt angle of the highway PV on electricity generation (Table S8 in Supporting Information S1). Panels tilted at a ten-degree angle produce 233 TWh (0.76%) less per year than horizontally fixed panels, but this loss can be offset by the benefit of soil removal by precipitation on the tilted panels (Li et al., 2020). The annual production of solar panels tilted at the latitude-dependent angles (Jacobson & Jadhav, 2018) is much less since these angles are optimal only for panels facing the equator. The efficiency of electricity generation exhibits significant variability across different climate classifications, as well as notable latitudinal and longitudinal variations (Figure S12 in Supporting Information S1).

We analyze the economic feasibility of developing highway PV worldwide based on LCOE and discover conspicuous spatial variability (Figure 2c). The global LCOE values range from US$44 to US$380 MWh^{-1}, with the majority (56%) in the range of US$60–120 MWh^{-1} (Figure 2d). The spatial pattern of LCOE is consistent with previous studies (Bódis et al., 2019; Joshi et al., 2021). In Europe, LCOE exhibits an increasing trend from low to high latitudes because attainable electricity per unit of capacity decreases with increasing latitude, but the required

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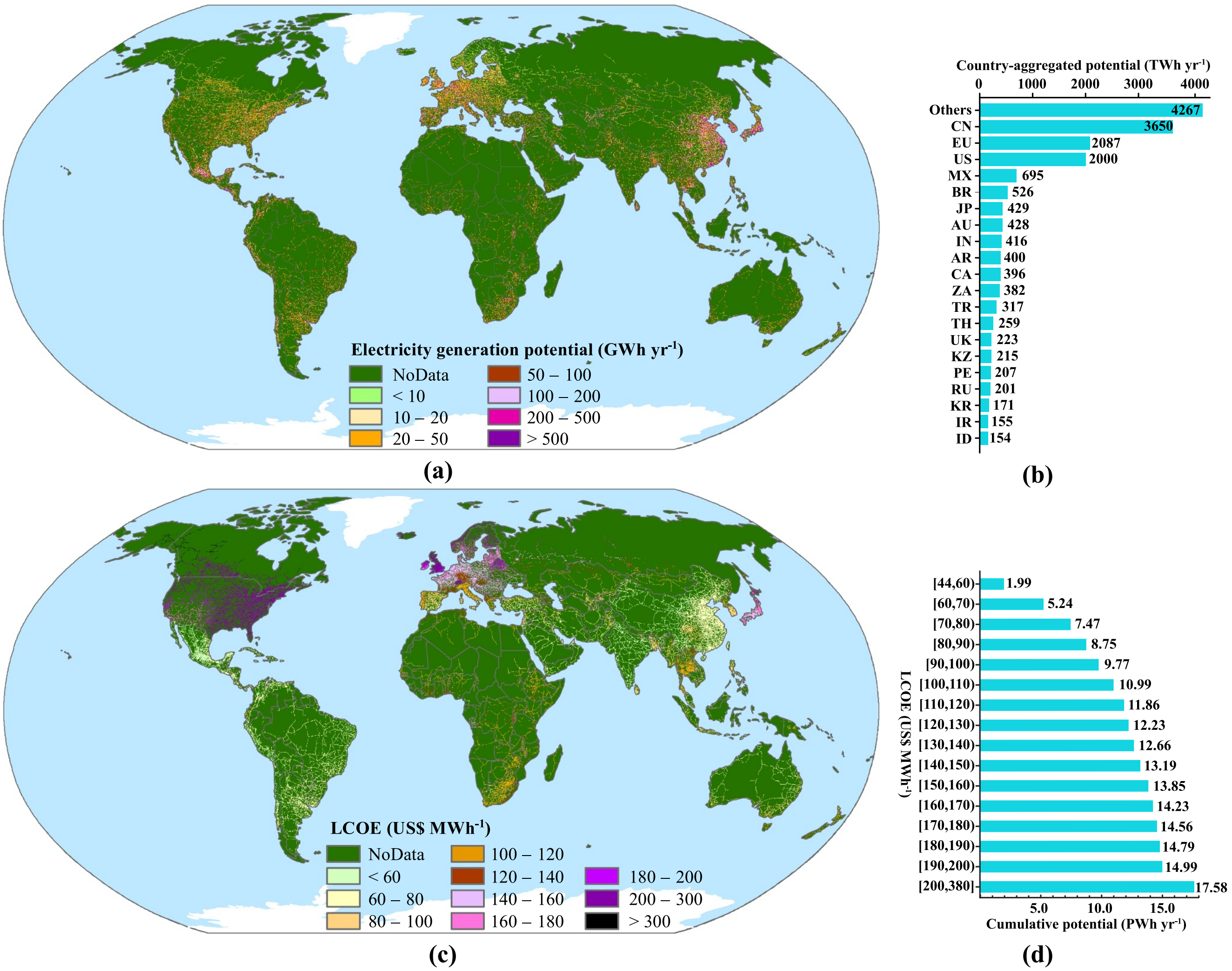

Figure 2. Electricity generation potential and levelized cost of electricity (LCOE) for the highway photovoltaics. (a, b) Global distribution (a) and country-aggregated sums (b) of the electricity generation potential. Note that 27 European Union countries are treated as a whole for the aggregation in (b). (c, d) Global distribution (c) and cumulative potential (d) of LCOE. The bar length represents the cumulative potential. LCOE bins increase with an increment of 10 from US\$60 to US\$200 MWh^{-1}, but LCOE values are aggregated into one bin when greater than US\$200 MWh^{-1} or lower than US\$60 MWh^{-1}. The absolute difference in length between two adjacent bars represents the increased potential that can be realized in the LCOE bin with a longer length.

investment remains almost invariant (Figure S3 and Table S3 in Supporting Information S1). In contrast, LCOE in eastern China shows a downward trend with increasing latitude due to higher cloud coverage in the south of China (Jiang et al., 2019; Sweerts et al., 2019). For Africa, countries along the Gulf of Guinea have higher costs to achieve their respective potentials primarily due to lower CFs (Figure S3 in Supporting Information S1). In the western hemisphere, there are large LCOE gaps (~US\$130 MWh^{-1}) between North America and Latin America, attributed to the distinct capital expenditures. Compared to ground-based PVs, the initial investments in the highway PV are slightly higher because of increased costs on support structures (Table S4 in Supporting Information S1).

Additionally, we investigate the possible increase in electricity generation by roofing solar panels over secondary roads with broader geographical coverage and higher density (Figure S1b in Supporting Information S1). The annual electricity generation of the secondary-road PV is 13,570 TWh, corresponding to an installed capacity of 10,191 GW. New hotspots for the secondary-road PV include India, Eastern Europe, Iran, and Brazil (Figure S13a in Supporting Information S1). US (2,478 TWh yr^{-1}) and India (1,343 TWh yr^{-1}) have the largest increase in electricity generation by adding installed capacities of 1,883 and 871 GW, respectively (Figures S11b and S13b in Supporting Information S1). By comparison, secondary-road PV is more competitive in India because of the

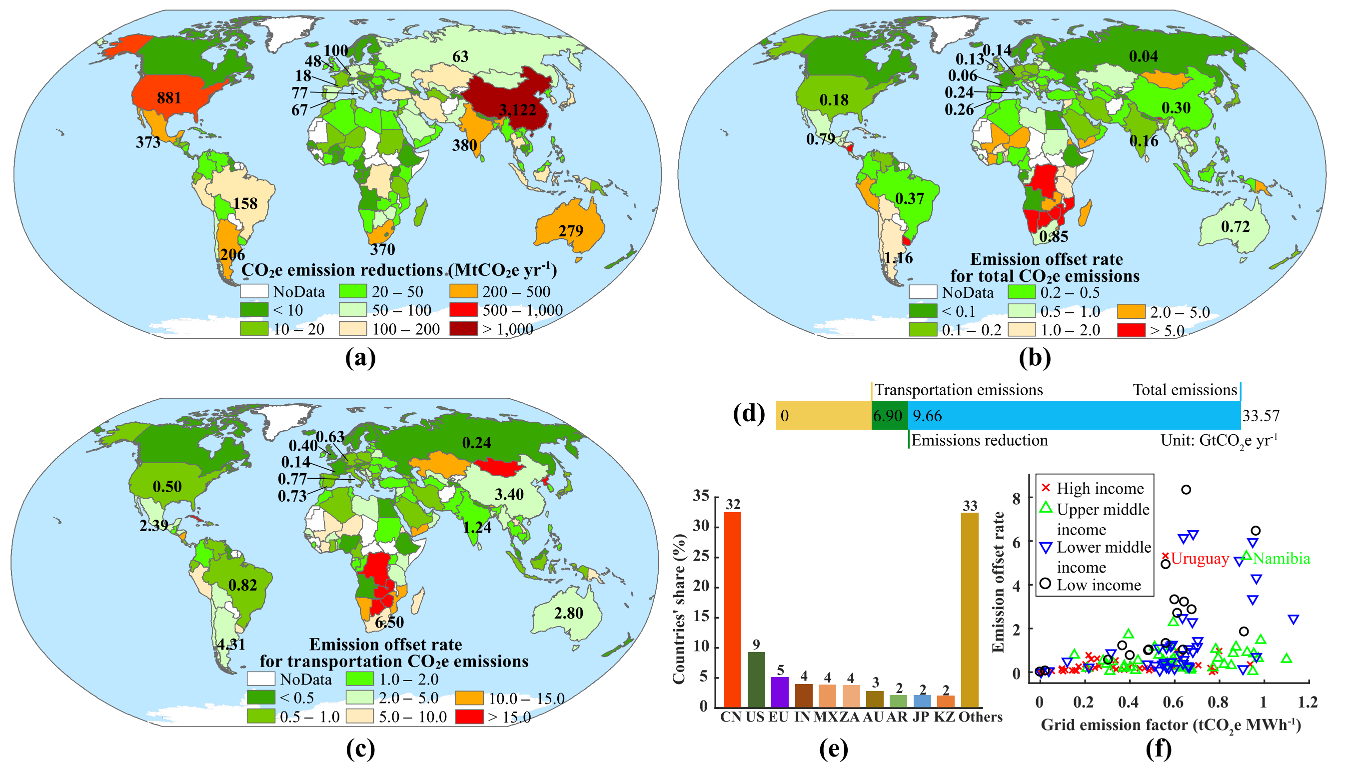

Figure 3. CO_2e emission reductions from the highway photovoltaics. (a) Aggregated CO_2e emission reductions at country levels. (b, c) Emission offset rate for total CO_2e emissions excluding land-use change and forestry (b) and for transportation CO_2e emissions (c). (d) Comparison between CO_2e emission reductions and total/transportation emissions on a global scale. (e) Top 10 countries' shares in the global total CO_2e emission reduction. (f) The relationship between emission offset rates for country-level total CO_2e emissions and grid emission factors for countries among four income country groups classified by the World Bank.

higher electricity generation per unit of installed capacity. The LCOE of the secondary-road PV exhibits a similar spatial pattern to that of the highway PV (Figure 2c and Figure S13c in Supporting Information S1). Nevertheless, the supply cost curve reveals that the average cost of the secondary-road PV is higher than that of the highway PV since the cumulative electricity generation grows faster when the LCOE exceeds US\$120 MWh^{-1} (Figure 2d and Figure S13d in Supporting Information S1).

3.2. CO_2e Emission Reductions

The electricity from the highway PV can be delivered to the grid to replace the electricity from fossil fuels, thus contributing to CO_2e emission reductions (Figure 1). These reductions (Figure 3a) are calculated by multiplying the amount of electricity generation by country-level grid emission factors (Equation 7). In addition, we calculate the emission offset rate (Figures 3b and 3c), defined as the ratio of CO_2e emission reductions by the highway PV to anthropogenic emissions, to identify the contribution of the highway PV to carbon neutrality (Equation 8). Overall, the global highway PV has a capability of reducing CO_2e emissions by 9.66 (9.47–9.77) $GtCO_2e$ yr^{-1} (Figure 3d). In 2018, the global total CO_2e emissions excluding land-use change and forestry (Figure S6a in Supporting Information S1) were 33.57 $GtCO_2e$ and the independent CO_2e emissions from transportation (Figure S6b in Supporting Information S1) were 6.90 $GtCO_2e$ (Climate Watch, 2022). With reference to both emissions, tapping the full potential of the highway PV can offset approximately 28.78% (28.21%–29.10%) of the global total emissions and completely neutralize the carbon emissions from the transportation system.

China and the US are the two countries that emit the most CO_2, together accounting for about 45% of global emissions in 2018 (Climate Watch, 2022) (Figure S6a in Supporting Information S1). Accordingly, they can reduce their emissions the most. China leads and contributes 3,122 (3,084–3,163) $MtCO_2e$ yr^{-1} (32%), and the US follows and contributes 881 (869–892) $MtCO_2e$ yr^{-1} (9%) (Figures 3a and 3e and Figure S14 in Supporting Information S1). Nevertheless, their current emission structures differ significantly, with China's total CO_2e emissions being twice as high as those of the US and China's transportation CO_2e emissions being about half those of the US (Figure S6 in Supporting Information S1). Therefore, the difference between China and the US is not evident in terms of their emission offset rates for the total CO_2e emissions, but China's emission offset rate for transportation CO_2e emissions is six times higher than that of the US (Figures 3b and 3c). Obvious contrasts are found in CO_2e emission reductions within the EU, reflecting the different progress of energy transition across the EU countries (Mata Pérez et al., 2019). Among the world's major emitters, only China and India can achieve reductions in CO_2 emissions through highway PV power generation that exceed the emissions from the transportation sector. This situation is improved by developing the secondary-road PV, which increases global CO_2e emission reductions to about 16.98 $GtCO_2$e yr^{-1}, allowing most countries to offset the CO_2 emissions from their transportation sectors completely (Figure S15 in Supporting Information S1).

We find considerable variabilities in emission offset rates for total CO_2e emissions among four income country groups classified by the World Bank (Figure 3f). Countries with high emission offset rates usually belong to low- and lower-middle-income groups that feature high grid emission factors (Figure S4 in Supporting Information S1). The exceptions are Uruguay and Namibia, whose primary economic sources are agriculture, livestock, and fishery, rather than industry (Kiesel et al., 2022; Piaggio et al., 2017), leading to their low emissions and high incomes. Emission offset rates are generally low in high-income countries, where the relatively high proportion of renewable electricity results in low grid emission factors (Tian et al., 2022) and, therefore, low CO_2e emission reductions from the highway PV. Most upper-middle-income countries have moderate grid emission factors and emission offset rates. These findings remain unchanged if the emission offset rates for transportation are considered (Figure S16 in Supporting Information S1).

3.3. Reduced Traffic Losses

The highway PV can immensely diminish the traffic accident risk induced by adverse weather, thereby reducing traffic losses (Figure 1). We evaluate the impact of road weather conditions and driving speed on the traffic accident risk and establish a probabilistic model to decompose country-level road traffic losses to the grid-box-level ones that are further assigned to various road types and weathers. Globally, we estimate that highway PV reduces road traffic deaths by 145,413 per year and socio-economic burdens by approximately US$426.6 ± 161.7 billion per year (Figure 4). These figures imply a 10.8% reduction in current road traffic deaths (WHO, 2018) and a 17.0% ± 0.3% decline in socio-economic burdens (Chen et al., 2019; Wijnen & Stipdonk, 2016). Further development of the secondary-road PV pushes these figures up to 316,815 per year and US$916.8 ± 302.6 billion per year (Figure S17 in Supporting Information S1).

Spatially, the reduction in deaths is mainly concentrated in accident-prone areas with high-density highways, such as eastern China, South Korea, Thailand, and Bangladesh, where at least one death per year is prevented per grid-box (Figure 4a). The largest reduction occurs in China, amounting to 63,604 and accounting for 44% of the global total reductions, followed by India (11,430, 29%), US (4,579, 8%), and EU countries (3,962, 7%) (Figures 4a and 4b). Among the four World Bank income groups, the mortality from highway accidents is generally high in low-income countries, but their reduction rates (reduced deaths divided by current deaths) are relatively low (Figure 4c) because their highway networks are underdeveloped and thus highway PV installations are limited (Figures S1a and S11a in Supporting Information S1). From the low-income group to the high-income one, the deaths per million decrease on average from 278, 206, and 180 to 83, respectively, while the reduction rate increases from 5.9%, 7.0%, and 13.4%–17.3%, respectively.

The spatial pattern of the reduced socio-economic burdens differs greatly from that of the reduced traffic deaths (Figures 4a and 4d) due to the distinct socio-economic development levels. US benefits the most (US$147.8 billion, 34%), followed by China (US$131.4 billion, 30%) and EU countries (US$42.9 billion, 10%) (Figure 4e). In the developed countries, the mortality-related medical costs and production losses are high (Bougna et al., 2022; Chen et al., 2019), and thus a tiny reduction in deaths can bring large socio-economic benefits. As for China, the vast reductions in the burdens are mainly attributed to the massive reductions in deaths. High-income countries initially have to take on high socio-economic burdens (US$792 per head), but with panel-roofed highways, the burdens can decline by US$150 per head (Figure 4f). In contrast, the burdens per head in the upper-middle-, lower-middle- and low-income countries are US$165, US$68, and US$17, respectively, which can be reduced by US$23, US$7 and US$0.9 owing to highway PV.

It is worth noting that there is a substantial distinction in reduced traffic losses across regions due to their contrasting weathers (Figures 4a and 4d and Figure S9 in Supporting Information S1). In Europe, larger reductions

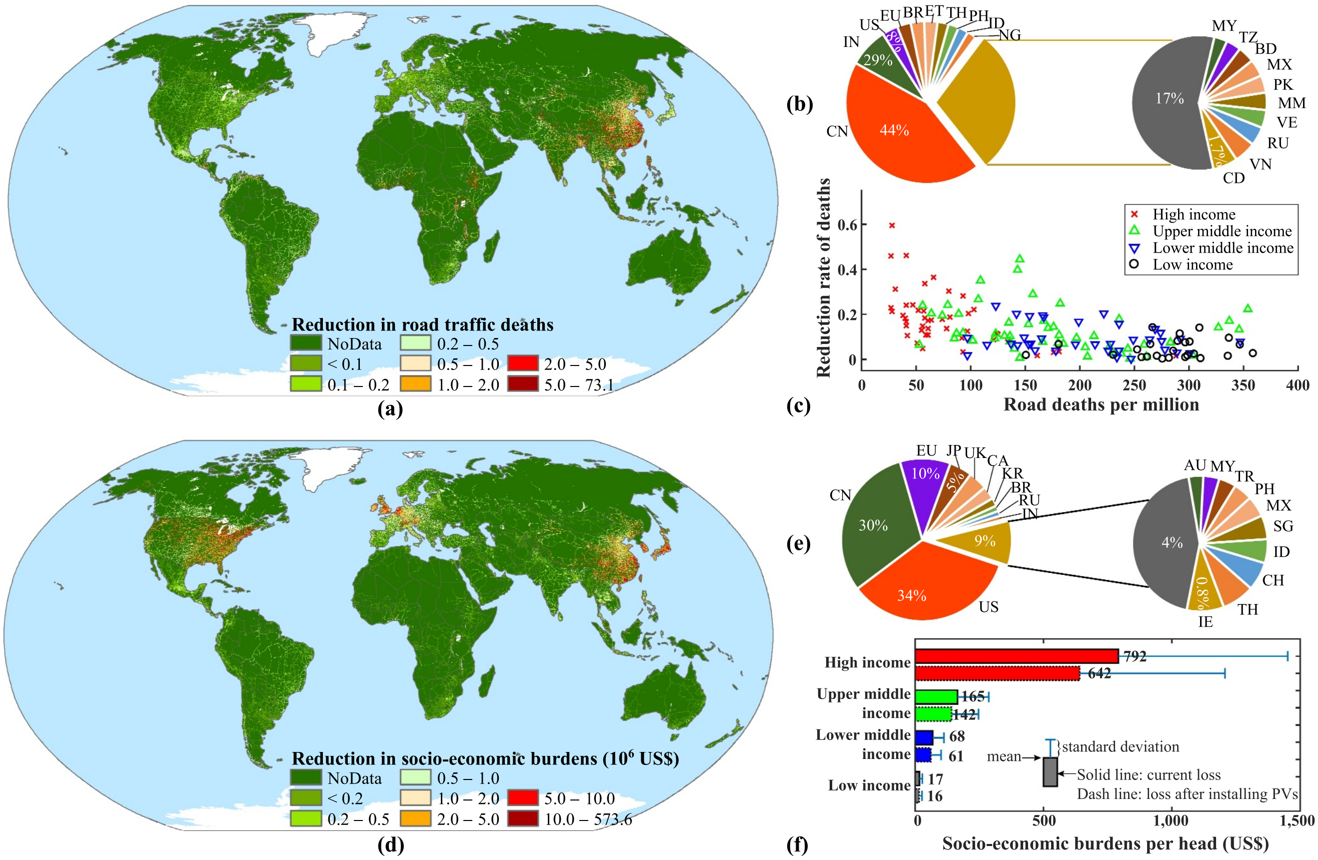

Figure 4. Reduced traffic losses through the highway photovoltaics (PV). (a, b) Global distribution of reductions in road traffic deaths (a) and the country-level proportions in the global total reduction (b). (c) The relationship between the mortality of road traffic accidents and reduction rates (reduced deaths divided by current deaths) for countries among four income country groups classified by the World Bank. (d, e) Global distribution of reductions in socio-economic burdens (d) and the country-level proportions in the global total reduction (e). (f) Socio-economic burdens per head before and after developing the highway PV for the four income country groups.

are available for countries with a higher probability of precipitation, such as the United Kingdom, the Netherlands, Belgium, and Germany. A similar situation also occurs within individual countries. For instance, the rainy southern regions of China have larger reductions than the sunny northern China. For the secondary-road PV, the largest increase in the death reduction happens in India and China (50,599 and 22,593, respectively), whereas the greatest benefits of reducing socio-economic burdens are obtained by US and China (US$278.6 billion and US $46.7 billion, respectively) (Figure S17 in Supporting Information S1).

4. Discussions

4.1. Investments and Returns

Our assessment reveals that highway PV can generate tremendous amounts of electricity and bring huge co-benefits by reducing both CO_2e emissions and traffic losses. However, countries with diverse incomes exhibit significant differences in co-benefits because of their distinct socio-economic development levels. Therefore, when developing the highway PV, tailored policies should be formulated according to local conditions. To guide the development, we analyze investments and returns for the highway PV over a 25-year lifetime on global and continental scales (Equation 13).

Globally, the former 50% of the cumulative potential can be achieved with an investment equal to 15% of the global GDP in 2020 (Figure 5a), which is 4.7 times the total investments in renewables during 2010–2019, or 57% of the projected cumulative investments as of 2050 at the current growth rate (Figure S18 in Supporting Information S1). Investing in the global highway PV will ultimately bring a NP of US$14.42 ± 4.04 trillion during a

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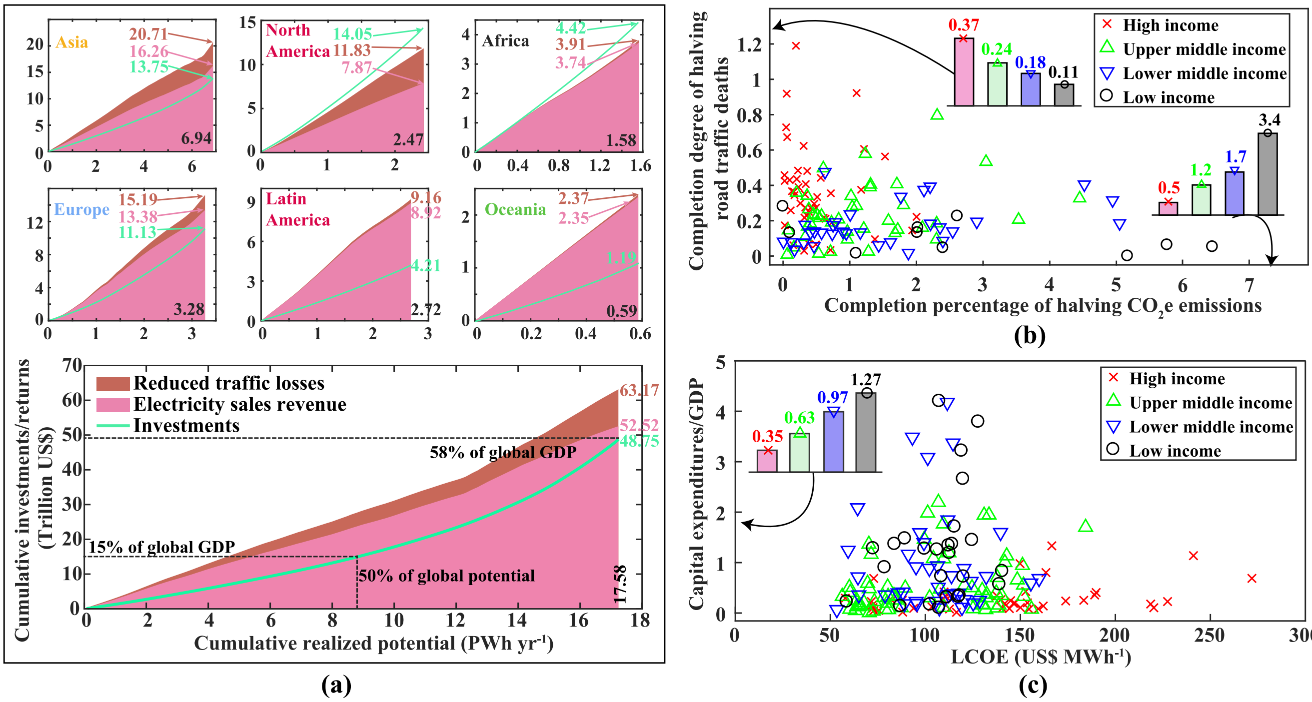

Figure 5. Investments and returns of the highway photovoltaics (PV). (a) Investments required to realize a specific potential and the corresponding returns from selling electricity and reducing traffic losses over a 25-year lifetime. We assume that the potential is realized according to levelized cost of electricity values from low to high, with the 2020 gross domestic product (GDP) data as a reference. The seven subfigures illustrate the results for the six continents and on a global scale. The investment includes capital expenditures, and operation and maintenance (O&M) expenditures, while the return includes revenue from electricity sales and reduced traffic losses. (b) Completion percentage of Sustainable Development Goals (SDGs) 3.6 and 7.2 of individual countries halving their respective CO_2e emissions and road traffic deaths through developing the highway PV. The two inset bar charts illustrate the averaged completion percentages for SDGs 3.6 and 7.2, respectively, among four income country groups classified by the World Bank. (c) Disparity in economic pressures (capital expenditures divided by the 2020 GDP) for realizing the full potential among the four income country groups. The inset bar chart illustrates the averaged pressures for the four groups.

25-year lifetime. If the extra returns from CO_2e emission reductions are taken into account, the 25-year NP increases by US$0.48 ± 0.24 trillion. As to the secondary-road PV, regions with low LCOE values (e.g., India, Iran, and Latin America) are worth developing because about 12% of 2020 GDP can realize 50% of the potential (Figure S19 in Supporting Information S1). At the continental scale, the highway PV projects are appealing in Asia and Europe given their tremendous net profits of US$6.96 trillion and US$4.06 trillion, respectively, and also of interest in Oceania and Latin America in view of the high profit per unit of electricity (Figure 5a). In Asia and Europe, government supports are required because a large portion of the profits originate from social benefits (reduced traffic losses).

In addition to the economic returns, highway PV can play a great role in achieving SDGs 3.6 (halving global road traffic deaths) and 7.2 (halving global CO_2e emissions). The full exploitation of the global highway PV potential can accomplish approximately 22% of SDG 3.6% and 57% of SDG 7.2 (Figures 3 and 4). Here, we further examine the completion percentage of individual countries halving their respective CO_2e emissions and road traffic deaths if the highway PV is fully developed (Figure 5b). Generally, high-income countries have an advantage of reducing road traffic deaths with an averaged completion percentage of 37%, while the highway PV in low-income countries is more conducive to reducing CO_2e emissions with an averaged completion percentage of 340%. If developing the highway PV, countries with different incomes have to take on distinct economic pressures (Figure 5c). Low- and lower-middle-income countries are confronted with 3–4 times the pressure of high-income countries and thus urgently need international cooperation. The ratio of capital expenditures to the 2020 GDP exceeds one for most of the low- and lower-middle-income countries, meaning that achieving the full potential in the first year is unaffordable for them. One solution may be to develop highway PV by learning form the experience of the CDM, which allows a country with emission-reduction or emission-limitation commitment to implement emission-reduction projects in developing countries. Similarly, highway PV projects in low-income countries can earn certified emission reduction (CER) credits and sell them to companies or other entities that emit excess CO_2.

4.2. Development Prospects

The highway PV system acts as not only a pure power plant but also a comprehensive solution for the global sustainability with specific advantages over other PV-based schemes in terms of land, water, ecology, and human well-being. The highway PV solution can align with SDGs 1 (no poverty), 3 (well-being), 7 (clean energy), 8 (economic growth), and 13 (climate action) by supplying solar electricity, decreasing CO_2e emissions, and reducing traffic losses (Table S9 in Supporting Information S1). Being a multi-objective composite nexus, the vitality of the highway PV stems from its convenient scalability and various added values. As highways themselves form networks and are spatially adjacent to the electricity grid, any electricity generated by the highway PV can be delivered through the grid to both local facilities (e.g., gas stations, rest areas, charging piles, etc.) and distant end consumers at relatively low costs. Highway expansion is associated with population growth (Meijer et al., 2018), which also facilitates the development of highway PV and the consumption of its generated electricity. Highway PV roofs can increase the life expectancy of road pavements by protecting them from precipitation and overheating (Ramos García & Castro, 2011) and shield surrounding residents from highway noise pollution by acting as barriers (Gu et al., 2012). Besides, the highway PV can also serve as "movable" charging piles for new energy vehicles on the road at any time (Yang et al., 2021).

Some efforts can be made to enhance the attractiveness and competitiveness of highway PV. First, roofing highways with solar panels is a particular technical challenge (Enkhardt, 2020; Steven, 2016). The support structures need to be optimally designed to protect the highway PV from the possible impacts of fast-moving vehicles underneath and simultaneously reduce the cost of the highway PV. Second, technologies such as electrostatic dust removal and automated dry cleaning systems (Farrokhi Derakhshandeh et al., 2021) should be explored and integrated to reduce the reliance on scarce water resources for cleaning PV panels in arid regions while maintaining cleanliness and power generation efficiency of PV modules. Third, connections have to be created between the highway PV and the grid to deliver the highway PV power to the end consumers. Fourth, forecasting and dispatching techniques need to be improved to strengthen the grid's ability to accommodate intermittent energy from the highway PV system (Qin et al., 2022). Fifth, reasonable market mechanisms should be established to monetize the co-benefits of the highway PV and reward its investors, thereby escalating the investment willingness of the entire community. Sixth, the highway PV ought to be scheduled in tandem with highway construction to reduce the initial installed costs, given that the added length of highways as of 2050 is projected to be 15.9%–25.3% of the existing length (Meijer et al., 2018). With these measures, the widespread use of highway PV will be made possible in the near future. We believe that the vision of pursuing carbon neutrality (Davis Steven et al., 2018) and achieving the SDGs (Schmidt-Traub et al., 2017) will make highway PV the next hotspot for renewable energy.

4.3. Uncertainties and Limitations

Through simulations and analyses, this study demonstrates that roofing highways with PV panels can substantially reduce carbon emissions and traffic losses. However, the quantitative results should be interpreted cautiously due to methodological simplifications and the presence of confounding factors that introduce uncertainties. First, the efficiency of PV electricity generation is notably influenced by climatic conditions, which vary geographically (Figure S12 in Supporting Information S1); thus, climate change is expected to induce spatially differentiated fluctuations in the highway PV potential. For instance, according to Lu et al. (2022), under the low-carbon Shared Socio-Economic Pathways, China's future PV power generation efficiency is projected to increase at a rate of 0.39% ± 0.01% per decade. Second, the emission reduction of PV generation is contingent upon its actual displacement of fossil-fuel-based electricity. The proportion of variable PV generation that the electric grid can accommodate is closely linked to regional power supply structures, grid efficiency, transmission losses, etc. Accurate emission reduction estimates, therefore, rely on sophisticated electricity dispatch models to obtain definitive values for R_c as outlined in Equation 7. Additionally, the carbon footprint associated with constructing the highway PV systems, which can be as high as 810 kg CO_2-eq/kWp over their life cycle (Müller et al., 2021), may negate up to 1.1 years of emission reduction benefits.

Regarding reduced traffic losses, this study hypothesizes that the installation of PVs over highways could eliminate rainfall runoff on these roadways. To achieve this, highway PV systems must be designed to effectively collect and redirect all runoff that falls directly onto the panels and ensure comprehensive coverage between panels. Regular maintenance is also crucial to maintain the proper functioning of these structures. Any deviation from ideal structural and maintenance conditions could result in an overestimation of the anticipated benefits. For instance, if the concentrated runoff generated by the solar roofs were to fall directly onto the highway surface, it would significantly increase driving risks. Furthermore, alterations in light and shadow patterns may affect the probability of traffic accidents. On one hand, a well-designed roof could shield drivers from direct sunlight and cause a decrease in visibility, particularly during sunrise and sunset, thereby reducing glare-related accidents. On the other hand, the installation of highway roofs may create a tunnel effect, increasing the likelihood of accidents. Although some pilot projects have shown that using translucent PV panels or installing LED lighting can mitigate changes to the driving environment (Hrapović, 2022), these projects are typically limited to stretches of less than 10 km, leaving the risks of long-distance driving under continuous highway solar roofs to be verified.

Besides, our assessment is limited by the accuracy of the global road inventories. Differences in road classifications and inconsistencies in road design standards may lead to uncertainties in highway PV generation potential. The limitation of the cost calculation is that LCOE cannot capture intra-country variations due to the lack of fine-grained statistics. Our investment analysis does not count the costs of upgrading the highways, constructing the support structures, and expanding the electric grid, as well as the returns from selling CER credits, increasing road pavement life, etc. Despite that, these limitations just lead to subtle differences in the presented values and do not conclusively alter the main findings (Figures S8, S14, and S17, Tables S2 and S8 in Supporting Information S1).

In addition, PV modules installed over highways may affect the thermal environment on the highway level by both absorbing and shading sunlight. The balance of these effects—increased heat from absorption versus decreased road surface temperature from shading—can vary with the efficiency of PV panels, their placement, and local weather conditions. The resulting temperature changes, in turn, affect the efficiency of vehicles and their cooling systems. However, quantifying these effects remains complex and requires comprehensive meteorological analysis, advanced simulations of radiation transfer, and vehicle thermodynamics. These topics present valuable directions for future research.

Data Availability Statement

Global road inventories can be acquired from the Global Roads Inventory Project (GRIP) (Meijer et al., 2018). Hourly data on solar radiation, ambient temperature, and precipitation type is available at the Copernicus Climate Change Service (C3S) Climate Date Store (CDS) (Hersbach et al., 2023). The capital expenditures are derived from the IRENA report (IRENA, 2021). The list of grid emission factors is available from the Institute for Global Environmental Strategies (IGES, 2021). The historical emission data are available at Climate Analysis Indicators Tool (CAIT) (Climate Watch, 2022). The global penetration rates are sourced from Our World in Data (Hannah & Pablo, 2020). The number of road traffic deaths are derived from the Global Status Report on Road Safety (WHO, 2018). GDP estimates in 2020 are obtained from the World Bank database at https://data.worldbank.org/indicator/NY.GDP.MKTP.KD. The electricity prices are sourced from the GlobalPetrolPrices.com at https://www.globalpetrolprices.com/electricity_prices/.

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