frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 25 January 2024
DOI 10.3389/fenrg.2024.1365532

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OPEN ACCESS

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RECEIVED 04 January 2024
ACCEPTED 15 January 2024
PUBLISHED 25 January 2024

CITATION
Liao Z, Zhang Y, Zhao X, Zhang Y, Liu M, Hong J and Cao H (2024), Comprehensive analysis of renewable hybrid energy systems in highway tunnels.
Front. Energy Res. 12:1365532.
doi: 10.3389/fenrg.2024.1365532

Comprehensive analysis of renewable hybrid energy systems in highway tunnels

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In order to explore the feasibility of a renewable hybrid energy system in highway tunnels, a scenario-coupled construction method for a highway tunnel renewable hybrid energy system is proposed. Based on this method, a tunnel on a highway in southern China serves as an example, and a renewable hybrid energy system for the highway tunnel is constructed. Using HOMER, the hybrid energy system is simulated, optimized, and analyzed, studying the characteristics of the operation of the highway tunnel hybrid renewable energy system in an off-grid mode. The optimal configuration for the hybrid energy system is proposed. The research results indicate the feasibility of constructing a highway tunnel renewable hybrid energy system by utilizing natural resources within the road area (solar energy, wind energy). The hybrid renewable energy system for this tunnel can provide 1112392 kWh of electrical energy annually, with the lowest energy cost being $0.17/kW. Furthermore, the hybrid energy system can reduce greenhouse gas emissions, contributing to the sustainable development of the environment.

KEYWORDS

road engineering, hybrid energy, homer, optimization configuration, feasibility, sustainability

1 Introduction

With the continuous development of the economy, the technology of highway traffic infrastructure is constantly improving (Jiang et al., 2022; Sun et al., 2023a; Sun et al., 2023b; Wang et al., 2023; Wu et al., 2024). The mileage of highways is also increasing continuously, and a considerable amount of electricity is consumed by highways each year. The existing energy supply for highways primarily relies on urban power grids, The pavement structure of highways has complex construction techniques (Büchner et al., 2019; K; Shi et al., 2024; Renken et al., 2018; Walther et al., 2019). Due to the extensive linear characteristics of highways, the conventional power grid transportation cost is exceptionally high. Moreover, the high dependence of highways on the power grid poses a significant risk; in case of power grid failure, the electricity supply to highways cannot be guaranteed. To avoid such issues, this study considers utilizing renewable resources within the highway domain to construct a scenario-coupled highway renewable hybrid energy system, exploring the feasibility of applying renewable hybrid energy systems on highways.

The highway domain encompasses abundant renewable energy resources. In the context of researching renewable energy within the available area of the highway domain (Liu and Fei, 2021), proposed a road photovoltaic prediction model. This model leverages remote sensing images and other geospatial information system (GIS) data to estimate the photovoltaic capacity of urban roads based on acquired urban characteristics (Ferri et al., 2022). evaluated the potential electricity generation of three different photovoltaic road materials and proposed a traffic shadow model (Duman and Guler, 2019). installed photovoltaic power generation equipment on both sides of the road, creating an off-grid system to supply power to road LED lighting devices. The study results indicated that the system is easy to maintain, installation is simple and fast, and it has a long lifespan (Rehman et al., 2020). introduced a method for assessing the solar potential of electric bus routes. The research findings suggest that installing solar panels on the roof of electric buses can offset approximately 8.5% of the power demand (Tian et al., 2020). utilized three-dimensional computational fluid dynamics (3D CFD) to numerically simulate wind turbines and turbine arrays on highways, investigating optimal rotor clearances (Sundaram et al., 2021). developed an off-grid vertical-axis wind turbine power generation system on highways, utilizing wind energy to power streetlights. Regarding road surface energy harvesting devices (Chen et al., 2021), proposed a road piezoelectric energy collection system, with research results indicating that the open-circuit voltage energy density can reach 15.37 J/(m.pass.lane) (Jiang et al., 2018). introduced a road thermoelectric generator system, where the module converts heat absorbed by asphalt surfaces into electrical energy, lowering the surface temperature. Experimental test results showed that the electrical output of a 300 mm × 300 mm × 100 mm asphalt surface can reach 0.564 V (Azam et al., 2021). designed a road energy harvesting device based on speed bumps. This device achieved a peak power of 11.99W and a peak voltage of 20.57V at a speed of 120 mm/s and a load of 150N (Yuan et al., 2023). proposed a road thermoelectric power generation system technology based on the Seebeck effect.

In the realm of technical research (Kotb et al., 2021), investigated the structure of the Wind/PV/Diesel/battery renewable hybrid energy system, considering factors such as load demand, storage costs, and interest rate varia

tions. Sensitivity analysis was conducted on the system. (Vendoti et al., 2021), studied the structure of the PV/Wind/Biomass/Biogas/Fuel Cell/battery renewable hybrid energy system under off-grid conditions, evaluating its economic and technical aspects (Das et al., 2021b). explored the PV/Diesel/Pump-hydro storage (PHS) renewable hybrid energy system, conducting sensitivity analysis on the system using variables such as solar radiation, diesel prices, PHS prices, and interest rates (Azerefegn et al., 2020). researched the structure of the Diesel/PV/battery hybrid energy system under grid-connected conditions and conducted sensitivity analysis on the system considering factors such as solar radiation, PV capital costs, grid electricity prices, load demand, fuel prices, and grid interruptions.

In terms of economic research, the primary focus is on the impact of two indicators: Net Present Cost (NPC) and Cost Of Energy (COE) (Das et al., 2021a). studied the PV/Wind/Diesel/Battery system under off-grid and grid-connected modes, finding that the cost of the PV/Diesel/PHS system combination is higher than that of the PV/Diesel/Battery hybrid system, with an energy cost of 0.34$/kWh (Cano et al., 2020). investigated the structure of the PV/Hydro Kinetic Turbines (HKT)/Battery renewable hybrid energy generation system, and the results indicated an energy cost of

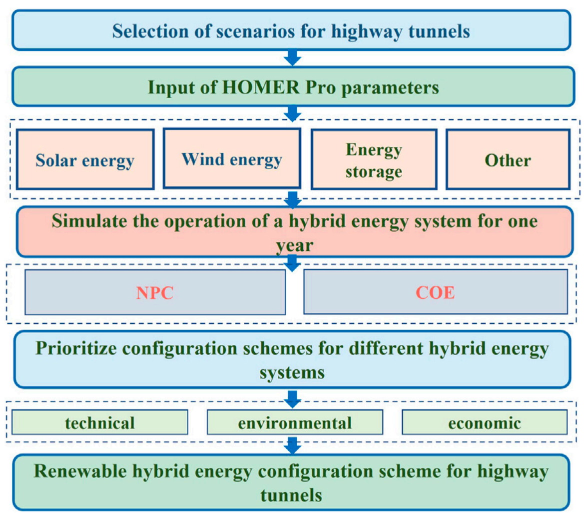

FIGURE 1
Flowchart of the Construction Method for the Highway Tunnel Renewable Hybrid Energy System.

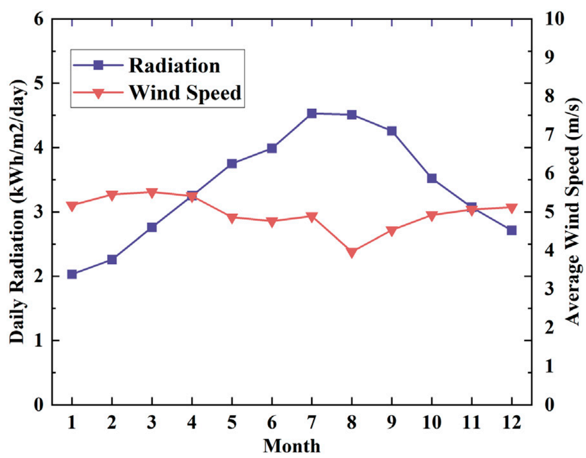

FIGURE 2
Solar Radiation and Wind Speed Data in the Case Area.

0.182$/kWh for the system (Li et al., 2020). examined the off-grid PV/Wind/Biomass hybrid renewable energy system, showing that the energy cost for this system is 0.182$/kWh (Coban et al., 2022). researched the structure of the Wind/Diesel/PV/battery grid-connected renewable hybrid energy system, revealing an energy cost of 0.182$/kWh for the system.

In summary, renewable hybrid energy systems have been widely applied in various fields, demonstrating good economic and technical feasibility. However, their application in the transportation sector is relatively limited. Therefore, this study considers the characteristics of highways, aiming to construct a scenario-coupled renewable hybrid energy system for highways. Using a tunnel on a highway in southern China as an example, the study analyzes the technical and economic feasibility of the highway's crucial energy nodes with a hybrid renewable energy system in off-grid mode.

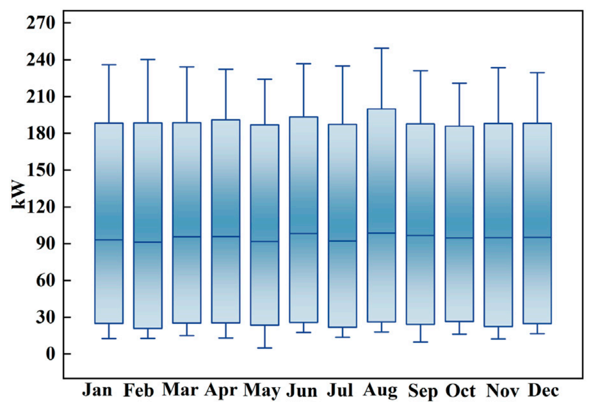

FIGURE 3
Distribution of Annual Electricity Consumption for Tunnel Main Loads.

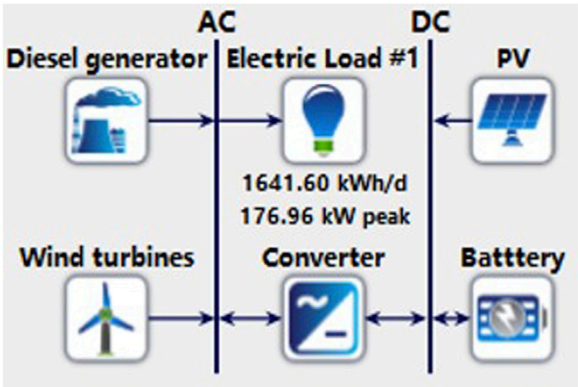

FIGURE 4
Schematic Diagram of the Tunnel Renewable Hybrid Energy System.

2 Tunnel renewable hybrid energy system construction method

The most widely used software in hybrid energy research is HOMER (developed by the U.S. National Renewable Energy Laboratory). It can simulate all possible combinations of hybrid energy systems based on inputs such as the distribution of annual electricity loads, resource data, technical and economic parameters of components, load data, and other project parameters. Following simulation optimization, different combinations are prioritized based on their cost, and a detailed technical and economic analysis is conducted for each system combination. This study primarily analyzes the utilization of renewable resources such as solar and wind energy in the areas where crucial energy nodes of highways are located. Through simulation optimization, hybrid energy solutions adaptable to highway scenarios are determined. The process flowchart of the construction method is shown in Figure 1.

Input for Multi-Scenario Coupled Highway Renewable Hybrid Energy System: The first step involves analyzing the renewable energy situation in the region where the highway is located, considering factors such as sunlight resources, wind resources, etc. The selection of renewable resources in the highway region is optimized, and data related to meteorology, economics, technology, electricity demand, etc., are collected. Meteorological data includes solar radiation, wind speed, and other relevant parameters.

Simulation and Optimization: Once the data input is complete, the system is simulated and optimized using HOMER. Under the condition of meeting the load demand, the system's operation is simulated for 1 year (8,760 h) to determine the feasibility of the hybrid energy solution. Optimization of the solution is based on the relevant cost parameters of each component in the renewable hybrid energy system. The optimization criterion is to minimize the Net Present Cost (NPC). After simulation and optimization, HOMER ranks different hybrid energy solutions based on the minimum NPC, providing a list of feasible solutions.

3 Case study

Case Location: The case study tunnel is located in the southern part of China at 24°43′12″N latitude and 109°48′56″E longitude.

Assessment of Utilizable Natural Resources: The case tunnel benefits from favorable wind and sunlight resources. Data on solar energy resources, wind speed, and other relevant parameters are sourced from NASA (National Aeronautics and Space Administration) (The period from July 1983 to June 2005.)and survey and design materials, as shown in Figure 2.

As indicated in Figure 2, solar radiation is higher in July and August each year, while it is lower in January and December. The maximum solar radiation is 4.5 kWh/m2/day, and the minimum solar radiation is 2.0 kWh/m2/day. The wind speed exhibits relatively stable variations throughout the year, with an average speed of 3 m/s.

Based on the assessment of utilizable resources mentioned above, this study considers constructing a scenario-coupled renewable hybrid energy system for the highway, utilizing the wind and sunlight resources in the region.

3.1 Load demand

Actual load data for this location can be obtained through design documents. The annual load of the main electrical equipment for this highway tunnel is depicted in Figure 3. The graph indicates that the energy consumption range of the tunnel is between 30 and 200 kW, and there is relatively small monthly variation in energy consumption, with a low fluctuation in the energy consumption curve.

3.2 Design of the renewable hybrid energy system

Based on the analysis of natural resources in the area where the highway tunnel is located, the consideration is given to utilizing the wind and solar resources of this region to construct a hybrid energy system. Due to the intermittent nature of solar and wind energy, the power generation of photovoltaic panels and wind turbines is

TABLE 1 Input parameters of hybrid energy system components.

Component name	Cost ($)	Replacement cost ($)	Operation and maintenance ($)	Model	Life
Pv (Li et al., 2020)	1,000/kW	950/kW	10/year	Peimar SG200M5	25years
Diesel generator (Askari and Ameri, 2012; Uwineza et al., 2021)	750/kW	750/kW	1.34 ($/op. hour)	Generic 500 kW Fixed Capacity Genset	30,000 (Hour)
Battery (El-houari et al., 2021)	1,650	1,650	15	H2500 ($LiFePO_4$)	12years
Wind (Sharma et al., 2022)	997	997	150	Generic30 kW	20years
Converter (Shiroudi et al., 2012; He et al., 2018)	300	300	0	SG100k3	15years

TABLE 2 Optimized design of microgrid proposed by HOMER.

Serial number	Configuration plan	PV (kW)	Wind (kW)	Diesel generator (kW)	Battery (kWh)
Case-A	PV- wind- Diesel generator - Battery	805	7	500	150
Case-B	PV- Diesel generator- Battery	1,283	—	500	188
Case-C	Wind - Diesel generator - Battery	—	20	500	261
Case-D	Diesel generator - Battery	—	—	500	73
Case-E	PV- Wind - Diesel generator	2,111	24	500	—
Case-F	Wind - Diesel generator	—	36	500	—
Case-G	PV - Diesel generator	3,120	—	500	—
Case-H	Diesel generator	—	—	500	—

unstable. Therefore, to ensure a stable power supply, the addition of a diesel generator as a backup power source is considered in the system. At the same time, batteries act as energy storage units to maintain a stable voltage at the load end, and a converter is used for current conversion between AC and DC modes. The schematic diagram of the highway renewable hybrid energy system is shown in Figure 4.

3.3 Parameters of the renewable hybrid energy system

To analyze the capacity, environmental impact, and economic aspects of the hybrid energy system in the case of the highway tunnel area using HOMER Pro software, it is necessary to input relevant parameters for renewable energy system components. The technical and economic parameters for the selected components in this study were obtained from published literature or manufacturers. The parameters are shown in Table 1.

4 Results and discussion

After simulation calculations using HOMER Pro software, the results include eight hybrid energy configuration scenarios. Analyzing the technical, economic, and environmental aspects of different system compositions, the optimal system configuration is selected based on comprehensive considerations.

4.1 Technical analysis

Using HOMER for optimization analysis, in this study, the hybrid energy system of the case tunnel was examined, with all configurations being a combination of solar photovoltaic components, batteries, and diesel generators. Cost of Energy (COE) and Net Present Cost (NPC) are important indicators for evaluating hybrid energy systems. Through optimization calculations and analysis using HOMER Pro software, the hybrid system with the minimum COE and NPC is determined, thereby establishing the feasibility of the hybrid energy system configuration. HOMER software simulated over 40,000 configurations of energy hybrid systems to meet load demands and assessed eight different scenarios technically and economically, as shown in Table 2.

The electricity generation results of the eight different hybrid energy system combinations simulated by HOMER are presented in Figures 5A–H, showing the percentage of electricity generated by each power generation device in each hybrid energy system. The electricity produced by each combination serves two main purposes: providing power for electrical loads and storing surplus electricity when the system's electricity generation exceeds load demand.

4.2 Economic analysis

In HOMER Pro, the economic viability of each hybrid system was also assessed. Table 3 reveals that the Net Present Cost (NPC)

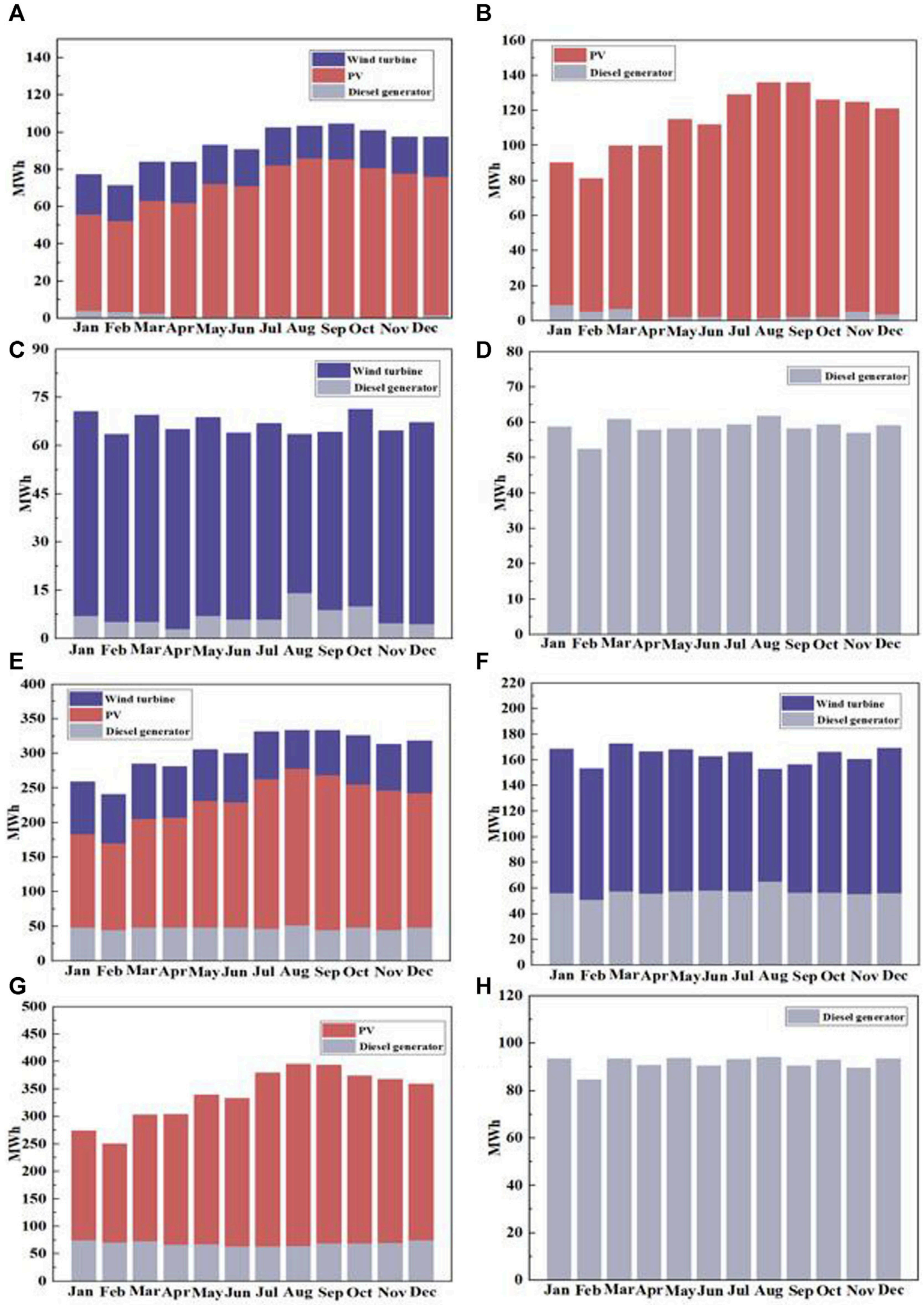

FIGURE 5
Power generation curve for each renewable hybrid energy system.

increases sequentially from case-A to case-H, with case-A having the minimum NPC value of $1,363,913, and case-H having the maximum NPC value of $7,986,208. From the perspective of energy cost, case-A has the lowest energy cost at $0.176/kWh.

4.3 Environmental analysis

HOMER Pro assessed the environmental impact of each hybrid energy system, and the results are presented in Table 4.

TABLE 3 Economic evaluation of each renewable hybrid energy option.

Serial number	NPC ($)	COE ($)	O&M ($)
Case-A	1363913	0.17	19184.67
Case-B	1522473	0.19	30963.81
Case-C	2070396	0.26	49105.64
Case-D	4358426	0.56	294335.8
Case-E	6101477	0.78	333560.1
Case-F	6329236	0.81	377294.1
Case-G	7426704	0.95	467025
Case-H	7986208	1.03	588760.3

The concept of penetration rate is defined as follows: the proportion of electricity demand served by the green energy generated throughout the year is called the Green Energy Penetration Rate (Renfrac). The calculation formula is given by Eq. 1:

$$Renfrac = \frac{P_{\text{ren}}}{L_{\text{served}}} \tag{1}$$

4.4 Determination of the optimal configuration

Based on the analysis of technical, economic, and environmental factors, case-A, case-B, and case-C are the top three ranked combination scenarios. Case-A's electricity is primarily generated by solar photovoltaic components, wind turbines, and batteries, making it the optimal combination with the best NPC, so Case-A is considered the best system configuration.

Table 5 shows the annual electricity generation of different renewable energy sources in the optimal combination. It can be observed that photovoltaic power generation contributes the most, accounting for 75.2%, while the contribution of diesel generators is the lowest, at 2.39%.

5 Conclusion

The paper focuses on the feasibility of constructing a hybrid energy system in the context of highway tunnels, particularly analyzing the potential for combining solar and wind energy within the highway tunnel environment. By leveraging the solar and wind resources available within the highway domain and considering the magnitude of the tunnel's electricity demand, an optimized calculation process identifies the optimal hybrid energy configuration. This proposed configuration aims to reduce carbon emissions from highway tunnels.

(1) The composition of the scenario-coupled renewable hybrid energy system for a highway tunnel needs to be determined based on the types of available energy scenarios in the region, including solar energy resources, wind resources, etc.
(2) Once the site selection and relevant energy conversion equipment parameters are determined, the Net Present Cost (NPC) and Cost of Energy (COE) serve as the primary indicators for evaluating the hybrid energy system. Simultaneously considering the emission of environmental pollutants from the hybrid energy system can assist decision-makers in selecting economically, environmentally friendly, and feasible renewable hybrid energy configuration schemes.

TABLE 4 Environmental impact assessment for each renewable hybrid energy option.

Serial number	CO_2(kg/yr)	CO(kg/yr)	HC(kg/yr)	PM(kg/yr)	SO_2(kg/yr)	NO_x (kg/yr)	Renfrac (%)
Case-A	20945	108	5.75	0.927	512	20.8	95.55
Case-B	36973	191	10.2	1.64	904	36.7	92.15
Case-C	68659	355	18.9	3.04	168	68.1	85.43
Case-D	477281	2,469	131	21.1	1,167	473	0
Case-E	456554	2,362	125	20.2	1,116	453	3.11
Case-F	539710	2,792	148	23.9	1,319	535	0
Case-G	650715	3,366	179	28.8	1,591	645	0
Case-H	867134	4,486	238	38.4	2,120	860	0

TABLE 5 Summary of annual power generation of different renewable energy sources.

Serial number	Assembly	Annual energy output (kWh/yr)	Percentage (%)
1	PV	836169	75.2
2	Diesel generator	26625	2.39
3	Wind turbines	249598	22.4
	total	1112392	100

(3) In this study, a highway tunnel in southern China was selected as a case. Through simulation and analysis from technical, economic, and environmental perspectives, the optimal renewable hybrid energy system configuration for this highway tunnel under the wind-solar scenario coupling was identified as PV-wind-Diesel generator-Battery. At this configuration, the system NPC and COE are $1,363,913 and $0.176/kWh, respectively. The annual emissions are as follows: 20,945 kg/year of CO_2, 108 kg/year of CO, and 512 kg/year of SO_2.
(4) Due to the influence of various uncertain variables on the renewable energy system for highways, future research can investigate the impact of uncertainties such as project lifecycle, interest rates, river flow rates, wind speeds, etc., on hybrid energy systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZL: Formal Analysis, Funding acquisition, Resources, Writing–review and editing. YfZ: Methodology, Project administration, Writing–original draft, Writing–review and editing. XZ: Writing–review and editing. YbZ: Writing–review and editing. ML: Investigation, Writing–original draft. JH: Data curation, Writing–review and editing. HC: Investigation, Supervision, Writing–original draft.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was sponsored by the National Key Research and Development Program of China (Grant No. 2021YFB1600200)、Guangxi Transportation Science and Technology Demonstration Project "Guilin-Zhongshan Highway Green Energy Self-consistent Supply and Efficient Utilization Key Technology Integration Application Research and Demonstration": 2023-0002 and Scientific Research Projects (21-53K, 21-36X) of Shaanxi Provincial Department of Transportation. The authors are grateful for the financial supports.

Conflict of interest

Authors ZL, YbZ, and ML were employed by Guangxi Communications Investment Group Corporation Ltd. Authors XZ and HC were employed by Shaanxi Transportation Planning and Design Institute Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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