

# A scheduling strategy for a new energy highway integrated network with clean green energy synergy

Clean green  
energy  
synergy

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## Abstract

**Purpose** – Green energy as a transportation supply trend is irreversible. In this paper, a highway energy supply system (HESS) evolution model is proposed to provide highway transportation vehicles and service facilities with a clean electricity supply and form a new model of a source-grid-load-storage-charge synergistic highway-PV-WT integrated system (HPWIS). This paper aims to improve the flexibility index of highways and increase CO<sub>2</sub> emission reduction of highways.

**Design/methodology/approach** – To maximize the integration potential, a new energy-generation, storage and information-integration station is established with a dynamic master-slave game model. The flexibility index is defined to evaluate the system ability to manage random fluctuations in power generation and load levels. Moreover, CO<sub>2</sub> emission reduction is also quantified. Finally, the Lianhuo Expressway is taken as an example to calculate emission reduction and flexibility.

**Findings** – The results show that through the application of the scheduling strategy to the HPWIS, the flexibility index of the Lianhuo Expressway increased by 29.17%, promoting a corresponding decrease in CO<sub>2</sub> emissions.

**Originality/value** – This paper proposed a new model to capture the evolution of the HESS, which provides highway transportation vehicles and service facilities with a clean electricity supply and



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achieves energy transfer aided by an energy storage system, thus forming a new model of a transportation energy system with source-grid-load-storage-charge synergy. An evaluation method is proposed to improve the air quality index through the coordination of new energy generation and environmental conditions, and dynamic configuration and dispatch are achieved with the master-slave game model.

**Keywords** HPWIS, HESS, NSIIS, Flexibility index, Energy generation, Storage and information integration station, Highway energy supply system, Highway-PV-WT integrated system

**Paper type** Research paper

### Nomenclature

PV	= photovoltaic;
WT	= wind turbine;
HPWIS	= highway-PV-WT integrated system;
HESS	= highway energy supply system;
NSIIS	= new energy-generation, storage and information-integration station;
$P_{s,t}^g$	= feed-in price of the NSIIS operator trading with the regional grid at moment $t$ ;
$P_{b,t}^g$	= purchase price of the NSIIS operator trading with the regional grid at moment $t$ ;
$q_t^{g,s}$	= electricity sold by the NSIIS operator to the regional grid at moment $t$ ;
$q_t^{g,b}$	= electricity purchased by the NSIIS operator to the regional grid at moment $t$ ;
$P_{b,t}^i$	= price of electricity sold within the system at moment $t$ ;
$P_{s,t}^i$	= price of electricity purchased within the system at moment $t$ ;
$q_t^{i,s}$	= amount of electricity sold by the NSIIS at moment $t$ ;
$q_t^{i,b}$	= amount of electricity purchased by the NSIIS at moment $t$ ;
$N$	= total number of NSIISs;
$p_b^i$	= internal purchase price;
$p_b^g$	= time-of-use price;
$p_s^i$	= internal sales price;
$p_s^g$	= on-grid price;
$r_{out}(i, t)$	= spare capacity that can be released by NSIIS $i$ at moment $t$ ;
$r_{in}(i, t)$	= spare capacity that can be stored by NSIIS $i$ at moment $t$ ;
$P_{PW}(i, t)$	= PV and WT output of NSIIS $i$ at moment $t$ ;
$P_{Grid}(i, t)$	= energy exchange between the grid and NSIIS $i$ at moment $t$ ;
$P_{load}(i, t)$	= load of the NSIIS $i$ section at moment $t$ ;
$P_{charge}(i, t)$	= charge power of NSIIS $i$ at moment $t$ ;
$P_{discharge}(i, t)$	= discharge power of NSIIS $i$ at moment $t$ ;
$SOC(i)$	= state of charge of NSIIS $i$ ;
$E_{bat}(i, t)$	= remaining power of NSIIS $i$ at moment $t$ ;
$C(i)$	= configured battery capacity of NSIIS $i$ ;
$flex(i)$	= flexibility index of NSIIS $i$ ;
$FLEX_A$	= flexibility index of the whole HPWIS A;
$E_{save}$	= potential for regional wind power generation;
$C_D$	= fuel consumption of diesel generator;
$\rho_D$	= density of diesel;
$C_C$	= emission factor of diesel; and
$S_S$	= area of different regions.

## 1. Introduction

In recent years, climate change mitigation has become one of the core tasks of governments, and an increasing number of countries have adopted the goal of carbon neutrality, transforming this objective into a national strategy and striving to build a carbon-free future (Yiyan, 2021). The transportation sector has remained that sector with the highest share of carbon emissions, and with the development of the transportation sector, this share is likely to continue to increase. The growth rate of carbon emissions in the transportation sector is slightly higher than that of total carbon emissions, and the share of carbon emissions in the construction and transportation sectors is slightly increasing (Hui, 2016). Within the context of the double-carbon target of China, the employment of new energy-generation facilities such as photovoltaics (PVs) and wind turbines (WTs) is crucial to unlocking emission reduction in terms of transportation.

To achieve this goal, the transportation industry, as the largest energy-consuming industry in China, has the notable task of saving energy and reducing emissions. According to total and forecast data of the International Renewable Energy Agency, by 2050, the proportion of renewable energy consumption will increase to 58%, while electricity consumption will increase to 33%, of which the proportion of electricity generated by renewable energy will reach 28% (R.E.N. 21 Renewables, 2021). With the rapid development of new energy technology, new energy generation continues to improve, the problem of new energy consumption gradually increases, and grid parity is achieved and gradually moving away from small-scale development and entering a new stage of development (Guoping *et al.*, 2020). This new type of energy generation differs from conventional power sources. Its power output is intermittent and random, and the transportation, especially the highway load, is uncertain and compulsive. Furthermore, the contradiction between the generation and requirements of renewable energy and transportation remains prominent.

There are two types of highways in China. One type is the Chinese standard high-grade highway, the construction technical standard level of which is higher than that of primary highways. The other type is the fully or semi-enclosed high-grade highway with unified designations by the Chinese Government (Yue, 2018). With a total of 5,198,100 km of roads and 160,100 km of expressways as of the end of 2020, China had built the largest expressway network in the world, covering approximately 99% of cities with urban populations of 200,000 people or more and prefecture-level administrative centers (Jianguo *et al.*, 2021). This extensive highway network requires a very large power supply to maintain normal operations, and in the future, there will be a widening gap in power demand as electric vehicles (EVs) are increasingly put into operation. In the past, new energy vehicles in China have exhibited a rapid development trend, and by the end of 2020, new energy vehicle ownership in China reached 4.92 million units, accounting, however, for only 1.75% of total vehicle ownership, while the sales of new energy vehicles in 2020 reached 1.367 million units, accounting for 5.4% of total new vehicle sales (Electricity Consumption and Production Supply, 2022). This number will continue to climb in the future. Integration with new energy and synergistic development with the environment by new pattern matching for land use and transportation supply and demand to improve transportation operational efficiency will become the prominent development method for transportation sectors in the future (Editorial Board of the Chinese Journal of Highways, 2016).

In the next step, the integration of renewable energy sources with highways and the installation of PVs and WTs on unused highway land is highly important for improving the flexibility of the energy supply of highway systems and the full cycle of CO<sub>2</sub> emission reduction. China has high potential for the development of new energy resources, with the national potential for wind and solar power development exceeding 3.5 billion and 6.1 billion kW, respectively, far exceeding the current scale of development (Guohui *et al.*, 2020; Lanxiang *et al.*, 2016). Therefore, PV and WT power generation are suitable choices for highway energy supply systems (HESSs).

In fact, the application of PV and WT systems along roads has been carried out for many years. In 2016, France established its first solar road in the village of Toulouvre, Orne, Normandy region, which is approximately 1 km long and 2 m wide and paved with 2,800 m<sup>2</sup> of solar panels (Zhipeng *et al.*, 2019). In China, in 2013, Xudong Cha's team at Changsha University of Technology designed a solar pavement hollow panel structure and built an outdoor model encompassing approximately 3 m<sup>2</sup> of solar pavement hollow panels in 2017. In 2016, the Hanergy Group constructed two solar bike paths in the Netherlands and Belgium. Regarding wind energy, renewable fuels produced from local wind power have been adopted as viable alternative fuels with which to reduce the consumption of petrol fuel in the road transport sector in Sweden (Siyal *et al.*, 2015). By replacing petrol fuel with domestic renewable fuel in the road transport sector, notable revenue and environmental savings have been achieved while also addressing the heavy reliance of the Swedish road transport sector on fossil fuel imports from neighboring countries (Siyal *et al.*, 2015). Apart from the above aspects, the configurations of wind and solar complementary power-generation systems and microgrids have been widely studied. The energy storage configuration problem of wind-solar complementary power-generation systems (Xiong *et al.*, 2021; Gangqiang *et al.*, 2021; Dong and Xianguo, 2019), the application problems of wind and solar complementary power-generation systems (Yanmei, 2020; Chenxi *et al.*, 2021; Jian, 2018) and the problem of the operational optimization of wind and solar complementary power-generation systems (Chendi *et al.*, 2016; Liu *et al.*, 2017a, 2017b; Li *et al.*, 2016a, 2016b; Lilan *et al.*, 2018) have been addressed and examined in detail. Among them, game theory, as a strategy through which to maximize self-interest without breaking market rules, has increasingly been applied to solve the multisubject interest equilibrium problem. Previous research has considered game theory in terms of energy, users and prices. In regard to the relationship between the power system and game theory, an economic performance efficiency-oriented mathematical model has been constructed (Chendi *et al.*, 2016), a model for multiple types of energy transactions considering multileader and multifollower game theory has been developed (Liu *et al.*, 2017a), both the operations system of new energy sources and energy management have been optimized with a master-slave game model (Li *et al.*, 2016a; Liu *et al.*, 2017b), a mathematical model for the multiple types of energy interactions between new energy sources and consumers has been proposed (Li *et al.*, 2016b), and a master-slave game model with community operators and generation and user sides as the main trading agents has been established (Li *et al.*, 2016b). However, these studies are not suitable for the new scenario of integrating new energy and highway transactors.

In the highway system in China, the long mileage, side ditches and available areas along highway lanes and the considerable area available in highway service areas clearly provide favorable conditions for PV and WT installation. With PV and WT installation along highways, the infrastructure and vehicle load on highways no longer depend on the grid alone but are supplied by new energy generation, storage and information integration stations (NSIISs) along highways. By analyzing the source, network, load, storage and charging characteristics of the highway system under the development scenario of grid and charging pile networks, the PV and WT energy resources of highway networks can be integrated. According to the relationship between the grid distribution and local highway power load conditions, 12 different scenarios with different configuration models are established, a four-component electricity distribution strategy is proposed, and a regional grid-based, single-leader multislave game dispatching strategy is applied to dispatching according to different operational models. Finally, with the Lianhuo Expressway as an example, the impacts of the new energy-highway integrated network and pollutant emission reduction are calculated. The results show that with PV and WT installation and the

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gradual construction of energy storage systems, the highway-PV-WT integrated system (HPWIS) and energy utilization can have a positive effect on CO<sub>2</sub> emission reduction and system flexibility.

## **2. New model for highway energy supply system of highway-photovoltaic-wind turbine integrated system**

HPWIS construction should be adapted to the environmental conditions of different highway systems. In the adaptation process, the HPWIS of Chinese highways can exhibit new characteristics in terms of system energy sources, networks, loads and storage and charging features. Therefore, a new environment-constrained HESS model is needed to consider the different characteristics of the HPWIS.

### *2.1 New features of highway-photovoltaic-wind turbine integrated system*

According to different environmental characteristics, the new energy integration of the highway system exhibits new characteristics of electrical energy supply sources. China's new energy resource development potential is large, and its energy strategic goals determining the future of new energy can still accelerate the large-scale development of new energy. After 2030, new energy will shift from alternative energy to the dominant energy transformation, and 2050 installed capacity of new energy power generation will account for more than 60% (Xunkui, 2021). According to the design pattern of Chinese highways, WTs can be installed on both sides of the highway roadside, and PV modules can be laid in the side ditches along the highway roadside and in highway service areas.

Under the evolution of the HPWIS, the HESS model is changing from the traditional uniform power supply of the grid to the interconnection of small independent new energy plants with the grid coordinated microgrid. As a result, the HESS also develops new network characteristics. Because the highway energy information system has new energy characteristics through highways, it is an important part of the adjustment of the highway energy information system to effectively use the new energy of the highway system.

With the change in the energy source and network characteristics of the highway system, the highway also shows obvious new characteristics in terms of electricity load, including mainly geographical distribution differences and strong temporal coupling. Depending on the abundance of solar and wind energy resources in the area where the highway is located, there can be significant differences in power generation and power load for each individual microgrid. The HPWIS has a clear temporal correlation, with higher PV generation in spring and summer and more significant WT output in winter; not only are the microgrid's energy needs met during these seasons, but surplus power is also brought online and hydrogen production is even achieved. At other times of the year when power generation is reduced, the microgrid needs to obtain power from the grid. As a result, the new HPWIS system load exhibits a clear temporal coupling characteristic with respect to the grid.

The HPWIS energy storage station consists of energy storage units and charging piles to store the electricity generated by each microgrid. Due to the decentralization of PV and WTs, the installation of the energy storage station needs to be decentralized and built according to the location of PV and WTs. For the highway system, the main energy use is in the form of tram-charging energy, so the main consideration is the large capacity of energy storage as the basis for selection. Combined with other factors such as efficiency, life and battery are undoubtedly the best choice, with the common battery types being lead batteries and nickel-cadmium batteries.

According to the China Charging Alliance (National Electric Vehicle Charging Infrastructure Operation), in September 2021, the number of public charging piles increased by 59,500 units in over the August 2021 level, with a 72.3% year-on-year increase. With the increasing number of sales of EVs, the annual sales of EVs in Beijing will reach 1.2 million units in 2030, and the charging load in residential areas will reach 210 kW, which will be difficult for the existing distribution grid to bear. However, with the increasing penetration of new energy vehicles and further construction of charging piles, if reasonable and orderly regulation is realized, fully using the dual attributes of the load source of EVs, then EVs not only can become a burden but can also provide the grid with valley filling, peak shaving, frequency regulation and standby services, and the new energy generation of the HPWIS can be fully consumed. HPWIS new energy generation can be better consumed to finally achieve the ideal charging state with full resource utilization, thus effectively improving the efficiency of the grid and charging facilities.

### *2.2 New highway energy supply system models of highway-photovoltaic-wind turbine integrated system*

The HPWIS with the adaptive adjustment of new energy and highway system energy use levels exhibits new features in terms of five aspects: power generation, transmission, storage, power use and charging. With the support of new information, communication and control technologies, the HPWIS operation and management mode can be gradually improved and developed in the direction of source, network, storage and charging synergistic regulation. The distribution of natural resources in China is extremely unbalanced, with energy- and power-generation centers in the central and western regions, while load centers are located in the better developed eastern regions of China. This pattern determines the long-term west-east power supply conditions needed to meet the higher power consumption in the eastern region and therefore governs power grid distribution in China. Moreover, the backbone power grid coverage density is high mainly in the eastern region, while Tibet, western Sichuan and southern Xinjiang mostly exhibit no backbone power grid coverage. In addition, the northwestern region contains abundant natural resources, but this region basically exhibits no power grid coverage. In China, power grids can be classified as strong, weak and end-of-pipe grids. Highway loads can be classified as high and low, and solar and wind resources can be classified jointly as abundant, average and scarce resources. Moreover, HESSs can be classified into 12 different scenarios based on regional grids, highway network loads and synergistic solar and wind resources. Different scenarios have different configuration models and strategies according to the different source, load, network, storage and charging conditions, as summarized in [Table 1](#).

## **3. Scheduling strategy and system evaluation of highway-photovoltaic-wind turbine integrated system**

### *3.1 Scheduling strategy of highway-photovoltaic-wind turbine integrated system*

The energy generated by each NSIIS of the HPWIS is dispatched according to a strategy involving chiefly self-consumption, followed by grid access or hydrogen production. The power difference at a given point is first calculated based on the PV and WT cogeneration potential and highway load, and the calculation then determines the battery state at the next moment. If the battery is fully charged or the maximum charging power is exceeded, then it is determined whether to go online or produce hydrogen with the residual power, respectively, based on the strength of the local grid. If the area is a strong-grid area, then the residual power is considered to go online. However, if the area is a weak-grid area, then grid access is first realized, after which hydrogen is produced. If the area is a no-grid area, then hydrogen is

Scenario no.	Characters	Scenarios	New models
1	Rich + small load + weak net	Xinjiang region	Renewable + energy storage + full self-use + hydrogen production from surplus electricity
2	General + small load + weak net	Tarim Basin, Jilin Province, Liaoning Province, Hainan Province, etc	Renewable + energy storage + full self-use + hydrogen production from surplus electricity
3	Rich + small load + no net	Tibet (except southeast), Northeast Inner Mongolia, etc	Renewable + microgrid + self-sufficiency + hydrogen production from residual electricity
4	General + small load + no net	Northeastern Heilongjiang Province, Southeast Tibet, etc	Renewable + microgrid + self-sufficiency + hydrogen production from residual electricity
5	Rich + small load + strong net	Central and West Inner Mongolia, Qinghai, Ningxia, North Gansu, North Yunnan, etc	Renewable + energy storage + microgrid + self-use + internet access
6	General + large load + strong net	Beijing, Tianjin, Hebei region	Renewable + energy storage + microgrid/power grid + mainly consumption + supplemented by power purchase
7	Scarcity + large load + strong net	East and South China	Renewable + energy storage + grid based + online power purchase
8	Scarcity + small load + strong net	Central China, Chongqing, Guizhou, etc	Renewable + energy storage + microgrid/power grid + self-use + supplemented by internet access
9	General + small load + strong net	Southern Gansu and southern Yunnan	Renewable + energy storage + microgrid + self-use + internet access
10	Rich + large load + strong net	East central region of North China	Renewable + energy storage + microgrid/power grid + mainly consumption + supplemented by power purchase
11	Scarcity + small load + weak net	Shaanxi Sichuan border	Renewable + energy storage + microgrid/power grid + full self-use + hydrogen production from surplus electricity
12	Scarcity + small load + no net	Western Sichuan	Renewable + microgrid + self-sufficiency + hydrogen production from residual electricity

**Table 1.**  
New models for the  
HESS of the HPWIS  
in different regions in  
China

produced with the residual power. Conversely, if the battery is not fully charged, then it is first determined whether the local NSIIS lacks power. If so, then power is purchased from the grid. Otherwise, energy dispatch is not performed between the local NSIIS and grid to ensure that the NSIIS achieves local power balance. To improve the energy dispatch efficiency of each NSIIS and fully manifest the flexibility of the microgrid, a master-slave game model can be applied to system energy dispatching. The NSIIS, as a comprehensive energy system, can realize the integration of production, supply and sales and the energy production-transmission-storage-consumption process, but when an imbalance between electricity production and demand occurs within the NSIIS, interaction with the outside environment is required to meet the power balance of the NSIIS. In the trading process, each NSIIS system comprises an independent generation system, storage, load, etc. In the operations optimization process, when the integrated energy system generates more power than the local electricity demand, the

excess power can be stored or sold to the upper-level NSIIS operator. In contrast, when the system power supply cannot satisfy local electricity demand, power is discharged by the energy storage device or purchased from the NSIIS operator. In the game process between the NSIIS operator and NSIIS as game participants, the NSIIS operator, as the leader, aggregates the power purchase and sale information of the lower-level NSIIS and sets power purchase and sale prices for the NSIIS at each moment during the next 24 h, with the objective function of maximizing revenue by combining the interaction tariff with the grid. Then, the NSIIS, as the follower, correspondingly sets power purchase and sale prices for system realization. The NSIIS operator and NSIIS exhibit a sequential order and influence each other, the game process of which is sequentially iterated until an equilibrium is reached. In the process of power trading, the settlement between the NSIIS operator and regional grid is based on the traditional time-sharing tariff with a benchmark feed-in tariff for coal-fired units. The settlement between the NSIIS operator and NSIIS is based on internal power sales and purchase prices. To encourage the NSIIS to participate in the internal power trading process of the system, the internal power purchase and sale prices should be more appropriate than the relevant grid electricity tariffs:

- (1) Participants. The NSIIS operator and NSIIS form a noncooperative master–slave game, playing the roles of leader and follower, respectively.
- (2) Strategy. In the game, the NSIIS operator uses the internal purchase and sale of electricity as a competitive strategy, choosing values that fluctuate within the space of its electricity strategy. In contrast, the NSIIS uses the purchase and sale of electricity and resource output as a competitive strategy, adopting values that fluctuate within the space of its electricity strategy.
- (3) Utility function. The NSIIS operator aims to optimize its economic benefits and correspondingly sets the utility function to achieve this goal. The NSIIS should consider environmental benefits while pursuing economic benefits and define operating and environmental cost minimization as its utility function:
  - Strategy. The gaming strategy of the NSIIS operator entails a multimoment power purchase tariff for participating integrated energy systems with the sale price of electricity.
  - Utility function. The NSIIS operator sets the utility function to optimize economic efficiency, covering mainly the cost of electricity purchased and the benefits of the electricity sold of the integrated energy system interacting with the regional grid, as shown in (1):

$$\max R^N = \sum_{t=1}^T \left( P_{s,t}^g q_t^{g,s} - P_{b,t}^g q_t^{g,b} + P_{b,t}^i \sum_{j=1}^N q_{j,t}^{i,b} - P_{s,t}^i \sum_{j=1}^N q_{j,t}^{i,s} \right) \quad (1)$$

where  $P_{s,t}^g$  and  $P_{b,t}^g$  denote the feed-in and purchase tariffs, respectively, of the NSIIS operator trading with the regional grid at moment  $t$ ;  $q_t^{g,s}$  and  $q_t^{g,b}$  denote the electricity sold by the NSIIS operator to the regional and purchasing grids at moment  $t$ ;  $P_{b,t}^i$  and  $P_{s,t}^i$  denote the prices of electricity sold and purchased, respectively, within the system at moment  $t$ ;  $q_t^{i,s}$  and  $q_t^{i,b}$  denote the amounts of electricity sold and purchased, respectively, by the NSIIS at moment  $t$ ; and  $N$  denotes the total number of NSIISs. To ensure a balance between supply and demand among NSIISs, the following equation should be satisfied:



$$\left\{ \begin{array}{l} q_t^g = \sum_{j=1}^N (q_{j,t}^{i,b} - q_{j,t}^{i,s}) \\ q_t^{g,b} = \begin{cases} q_t^g, q_t^g \geq 0 \\ 0, q_t^g < 0 \end{cases} \\ q_t^{g,s} = \begin{cases} -q_t^g, q_t^g < 0 \\ 0, q_t^g \geq 0 \end{cases} \end{array} \right. \quad (2)$$

where  $q_t^g < 0$  denotes the amount of electricity implemented by the NSIIS operator to interact with the main network after collecting electricity purchase and sale information from each NSIIS. When  $q_t^g > 0$ , the system power supply is limited, and the NSIIS operator must purchase power from the grid. Conversely, when  $q_t^g < 0$ , the system power supply is sufficient, and the NSIIS operator can sell electricity to the grid for profit.

- (4) Strategy space. To enhance the subjectivity of the NSIIS when trading with the NSIIS operator, the NSIIS operator should obtain the internal purchase price, and the electricity sale price should satisfy condition (3). That is, internal purchase price  $p_b^i$  shall not be greater than the time of use price  $p_b^g$ , and internal sales price  $p_s^i$  shall not be less than on-grid price  $p_s^g$ . When the integrated energy system seeks to minimize its own costs, it is more willing to participate in NSIIS transactions.

$$p_s^g \leq p_s^i \leq p_b^i \leq p_b^g \quad (3)$$

- (5) Notably, the internal power purchase price should be no higher than the time-sharing price, and the internal power sales price should be no lower than the feed-in tariff. The integrated energy system can better participate in the transactions of the NSIIS operator when it pursues cost minimization. The strategy space of the NSIIS operator is determined as in (3), and the specific steps are shown in [Figure 1](#).

Through the proposed energy-highway integrated system, decentralized scheduling with dynamic multileader and multipower game models can be accomplished. With the obtained time-sharing information, we can maximize the utilization of natural resources.

### 3.2 Definition of system evaluation indices

There are certain indices for evaluating the new HPWIS.

**3.2.1 Definition of resilience index.** The term “flexibility” describes the ability of an electric system to operate under generation and demand variability and uncertainty while maintaining a certain reliability level and reasonable cost over time. In the HPWIS, the variability and uncertainty in generation are assumed to originate from PV and WT systems. Diversity and uncertainty in new energy-generation systems promote the need for system flexibility. In the HPWIS, storage configuration is based

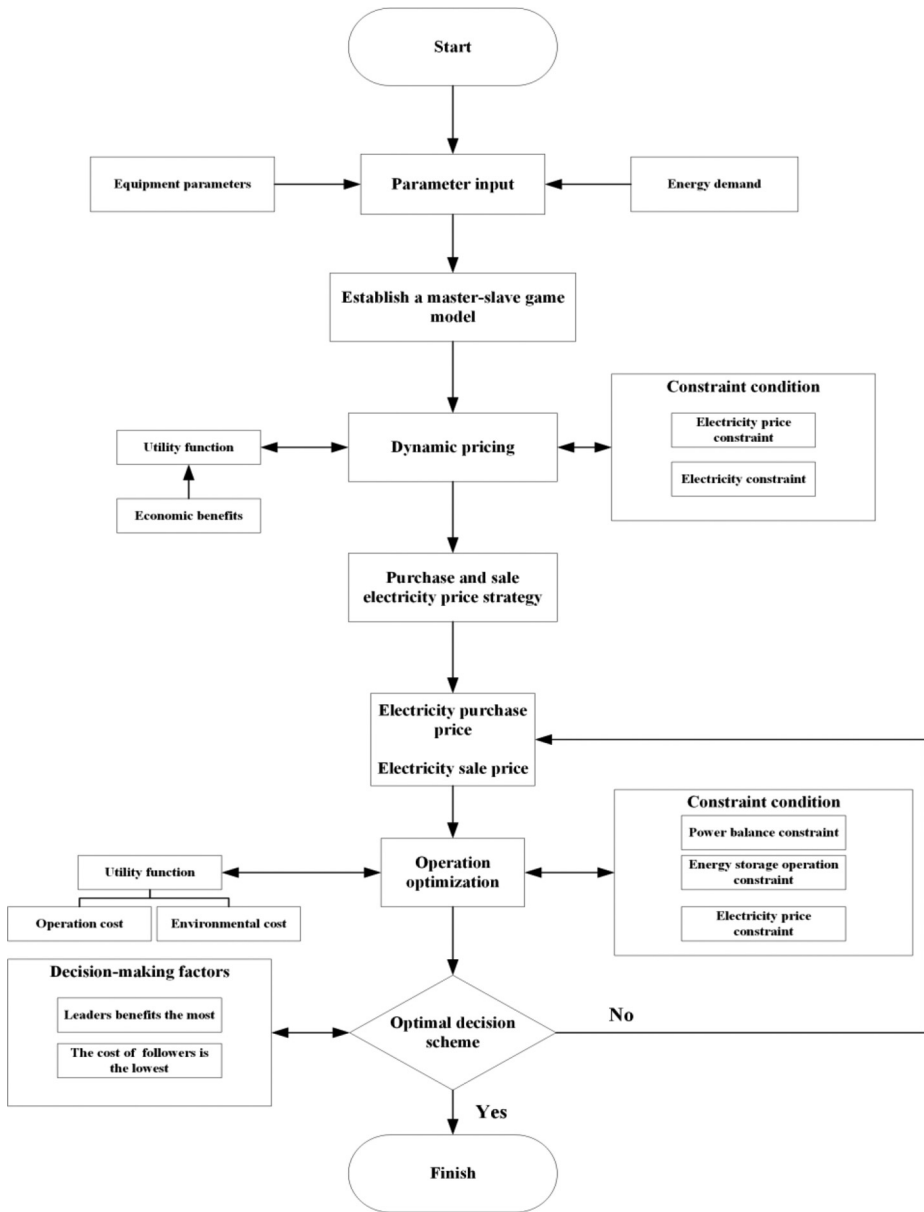


Figure 1.  
Master-slave game  
process of the NSIIS

on storage flexibility requirements. In this paper, an index criterion to measure flexibility in the HPWIS is proposed. Flexibility refers to the ability to determine the operation state of the HPWIS operator according to the variability and uncertainty requirements of generation and demand *Ma et al. (2013)*, the mathematical model of which is as follows:

$$\begin{aligned}
 0 \leq r_{out(i,t)} &\leq \max\{P_{PW(i,t)} + P_{discharge(i,t)} - P_{Grid(i,t)} - P_{load(i,t)}, 0\} \\
 0 \leq r_{in(i,t)} &\leq \max\{P_{charge(i,t)} - P_{PW(i,t)} + P_{Grid(i,t)} + P_{load(i,t)}, 0\} \\
 \forall i \in A, \forall t \in T.
 \end{aligned} \tag{4}$$

where  $r_{out(i,t)}$  and  $r_{in(i,t)}$  denote the remaining power that can be released and stored, respectively, by NSIIS  $i$  at moment  $t$ ; and  $P_{Grid(i,t)}$  is the magnitude of energy exchange between NSIIS  $i$  and the grid at moment  $t$ . The value is positive when the NSIIS actively delivers power to the grid, the value is negative when the NSIIS actively obtains power from the grid, and the value is zero when no power is actively exchanged. Moreover,  $N$  is the number of NSIISs in the HPWIS;  $P_{load(i,t)}$  is the load size of NSIIS segment  $i$  at moment  $t$ ; and  $P_{charge(i,t)}$  and  $P_{discharge(i,t)}$  are the charging and discharging power levels, respectively, of NSIIS  $i$  at moment  $t$ . For  $0 < SOC(i) < 1$ , the maximum charging and discharging power levels of the battery are  $P_{charge(i,t)}$  and  $P_{discharge(i,t)}$ , respectively. For  $SOC(i) = 1$ ,  $P_{charge(i,t)} = 0$ , and for  $SOC(i) = 0$ ,  $P_{discharge(i,t)} = 0$ .  $T$  is the total scheduling time (Ning *et al.*, 2021). Thus, the contribution of each NSIIS to flexibility is limited by its charging/discharging power, and the ability of the HPWIS to track changes in net demand and meet demand balance constraints is limited by the amount of power exchanged with the grid. The amount of power exchanged by the NSIIS with the grid and the battery charging/discharging power are metrics that define the ability of the NSIIS to provide flexibility, and the battery charging/discharging power level depends on the configured battery capacity. Based on the above aspects, flexibility parameters can be defined for each NSIIS. To enable a comparison, the parameters must be normalized as shown in (5):

$$\begin{aligned}
 flex(i) &= \{1/2[P_{charge(i,t)} + P_{discharge(i,t)} + P_{Grid(i,t)}]\} \times E_{bat(i,t)} \\
 &\div C(i), \forall i \in A
 \end{aligned} \tag{5}$$

where  $E_{bat(i,t)}$  is the residual power of NSIIS  $i$  at moment  $t$  and  $C(i)$  is the continuous cell capacity of NSIIS  $i$ . When calculating flexibility, the failure case is not considered, and therefore, the flexibility index of the whole HPWIS is defined as a weighted sum of the flexibility parameters of all NSIISs, as shown in (6):

$$FLEX_A = \sum_{i \in A} \left[ C(i) / \sum_{i \in A} C(i) \times flex(i) \right], \forall i \in A \tag{6}$$

where  $A$  denotes an HPWIS comprising several NSIISs with a weighting factor equal to the battery capacity contributed by each NSIIS. While road traffic operations and improvements can be very complex and variable, this parameter is not influenced by specific operational decisions. Therefore, this approach can suitably evaluate the HPWIS flexibility index under variable outputs and loads. Flexibility assessment is closely related to the energy storage capacity of each NSIIS and the dispatch strategy between NSIISs, which is described in the following two sections.

### 3.2.2 Definition of carbon emission reduction.

- The annual savings resulting from the purchase of electricity in the highway-based CO<sub>2</sub> emission reduction system is the amount of electrical energy substituted for new energy generation; in other words, for each unit of new energy generation consumed in the highway system, the corresponding emissions are reduced. Notably, the reduction in CO<sub>2</sub> emissions is related to the new energy-generation

potential. In regard to electrical energy substitution, the CO<sub>2</sub> reduction factor is regarded as 0.997 kg/kWh; i.e. each unit of electricity consumed can reduce carbon dioxide emissions by 0.997 kg. The formula for electric energy substitution emission reduction is as follows:

$$\begin{aligned} V_D &= E_{\text{save}} \times C_D \div \rho_D \\ E_{re} &= C_C \times V_D \end{aligned} \quad (7)$$

where  $C_D$  is the fuel consumption of the diesel generator, taking a value of 0.24/kg/kWh;  $\rho_D$  is the density of diesel, taking a value of 0.84 kg/L; and  $C_C$  is the emission factor of diesel, taking a value of 2.6765 kg/L.

- Carbon emission reduction via biological sinks: The simulated wind and solar farms can generate approximately 3 and 79 TW of electricity, respectively, on average in a typical year. Wind farms facilitate an increase in the near-surface air temperature, which leads to an increase in precipitation of approximately +0.25 mm/day, resulting in an increase in vegetation cover by 0.84%. Each additional hectare of broad leaf forestland absorbs an additional ton of CO<sub>2</sub> on a daily basis. Trees also absorb oxygen and expel carbon dioxide at night, but because the amount of carbon dioxide absorbed during the day is large, at almost 20 times larger than that at night, the side effects at night are relatively small compared to those during the day (Li *et al.*, 2018). The calculation formula of ecological restoration and emission reduction caused by the installation of new energy power-generation facilities is as follows:

$$E_{re} = E_{\text{save}} \times \varepsilon \times S_S \times 365 \quad (8)$$

where  $E_{\text{save}}$  is the potential of regional wind power generation;  $S_S$  is the area of different regions; and conversion coefficient is  $\varepsilon$  0.0028%/tw.

- Other emission reduction targets: According to the standard discount coefficient method of the National Energy Administration, each unit of electricity avoided can save 0.4 kg of standard coal and reduce carbon dust emissions by 0.272 kg, sulfur dioxide emissions by 0.03 kg and nitrogen oxide emissions by 0.015 kg.

#### 4. Lianhuo Expressway as case study for specific analysis

##### 4.1 Road traffic and energy integration scheme for Lianhuo Expressway (Xi'an-Urumqi)

The Lianhuo Expressway (Xi'an-Urumqi) is considered a typical case for calculation and illustration purposes. After the Gansu and Xinjiang resource-rich small-load strong and weak network area, due to the low highway load in this area, solar and wind energy resources sufficiently exist, and the wind-power-generation system can meet the load requirements. Therefore, this scheme is designed as land-based power generation with microgrid-led energy storage under surplus power transmission to the grid/hydrogen production and implemented as follows:

- PV layout: PV equipment is installed on both slope sides of the highway, side ditches (1.5 m on each side) and 70% of the service area. Fan installation: a single row of fans is installed on both sides of the highway, within 3–10 km of the road,

and with the service area as the center, fans are installed in a circle-like pattern with a radius of 3 km.

- The wind-solar complementary power-generation system generates electricity, and when load demand is lower than the power-generation level of this complementary power-generation system, the energy storage system is charged. When the energy storage device reaches its upper limit, the charging process is stopped to ensure storage device safety. When the generation capacity of the wind-solar complementary power-generation system cannot satisfy load demand, the energy storage device discharges stored energy to compensate for the required load difference, and the energy storage device enters a discharging state. In this power supply scheme, PV panels and WTs occupy a very large area, but the new energy power-generation level fluctuates greatly over time. Therefore, the capacity of the storage system should be increased to stabilize power fluctuations and improve the utilization of power-generation facilities. Eventually, the output can be maintained higher than the load to achieve stability of the power-generation system. Energy storage facilities can be centrally located at the substation of the corresponding power supply section.
- Wind- and solar-power-generation facilities are connected to substation energy storage units to establish a microgrid, thereby forming an NSIS cluster along the highway line. In each substation section, the power generated by PVs and WTs is introduced into the corresponding substation transformer through the busbar. WTs, PV units and battery packs are connected to a direct current (DC) bus for alternating current (AC)–DC conversion. The DC bus connects inverters and transformers to adjust the voltage level of electrical energy to the applicable level of AC power, which supplies the highway system in conjunction with the grid.

#### 4.2 Description of calculations

**4.2.1 Environmental impact calculations.** After preliminary calculations, the total annual load of the Lianhuo Expressway (Xi'an-Urumqi) is found to reach approximately 54,349,897,200 kWh, and the annual wind-solar power-generation potential is found to be 31,679,811,815 kWh, as shown in [Figure 2](#), under large-scale scenarios, which can facilitate self-consistency.

After the installation of PV equipment and fans on both slope sides of the highway and side ditches, emission reduction can be achieved via electrical energy replacement. Notably, carbon dioxide emissions can be reduced by 31,584,772 tons because the installation of new energy-generation facilities facilitates vegetation restoration, and consequently, emissions can be reduced by 6,229,354 tons, as shown in [Figure 3](#). Other emissions, such as carbon dust, sulfur dioxide and nitrogen oxide emissions, can be reduced by 8,616,909, 950,394 and 475,197 tons, respectively. The application of the NSIS network dispatch strategy further exploits the pollutant reduction potential of the HPWIS and achieves better environmental benefits. When wind-solar power output is high, self-consumption is prioritized, thus helping to avoid the purchase of power from the grid, and when output is low, the power stored in each microgrid is consumed, thus reducing CO<sub>2</sub> emissions in an all-round manner, in line with the current requirements.

At present, the double-reduction approach has become a major indicator requirement for the development of all industries. The integration of wind and solar energy resources with the road system can be an important way through which to achieve the double-carbon target. The electrification of roads via renewable energy is an important advancement in

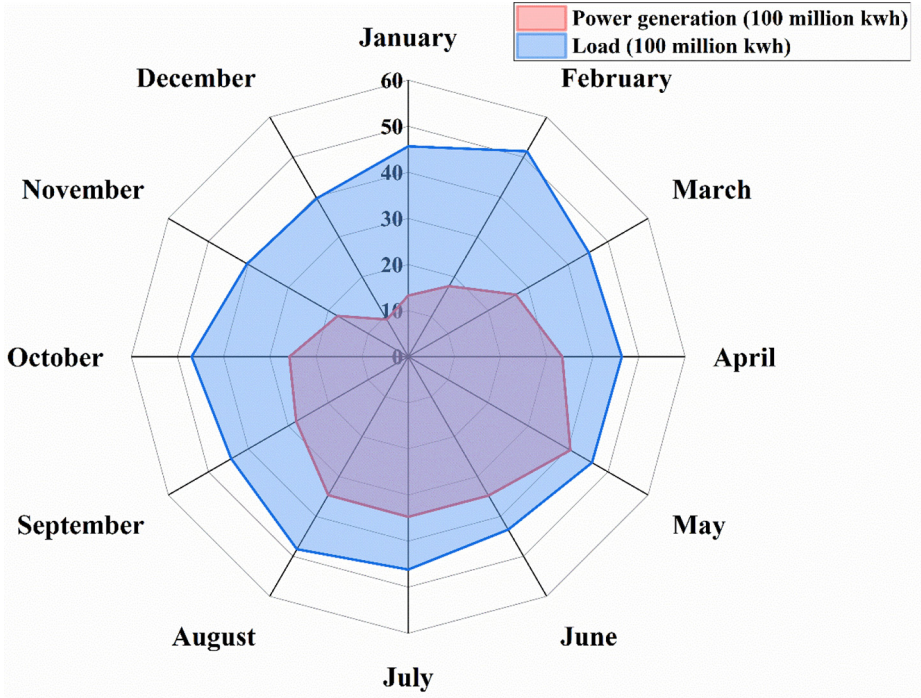


Figure 2.  
Comparison of power generation and load of Lianhuo Expressway

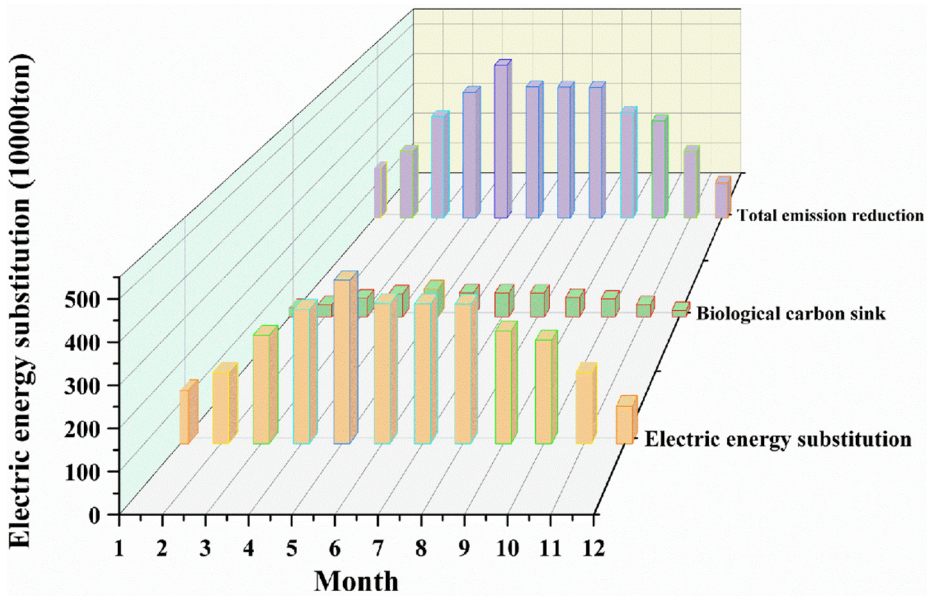


Figure 3.  
Comparison of the emission reduction of Lianhuo Expressway

transportation. This strategy can fully use not only renewable resources and reduce greenhouse emissions but also roadside areas, promoting local ecological restoration, thus achieving the goal of sustainable development. By introducing PV and WT power generation, highways can reduce their grid dependence, which not only promotes the development of new energy sources but also reduces grid load and the difficulty of HESS construction. Therefore, the three-in-one integrated PV-WT highway network model is a major research direction for future road transportation development. Calculations reveal that in the Xi'an to Urumqi section of the Lianhuo Expressway, with increasing construction of PVs, WTs and energy storage systems, the HPWIS can basically achieve self-consistency and a high penetration rate of new energy. The NSIIS can be applied to HESSs, and the dispatch strategy of the NSIIS network entails self-sufficiency first, followed by grid access/hydrogen production. In other words, each NSIIS is connected to the grid, and when the output is sufficient, the NSIIS can supply power to the local road system alone, and the remaining power can be considered for grid connection or hydrogen production depending on the strength of the local grid, thus avoiding the abandonment of wind and solar energy resources and simultaneously increasing profit. Based on the NSIIS system, many pollutant emissions can be reduced, constituting a new energy system with environmental constraints. In addition to providing highway power services, distributed PV and WT generation and energy storage scheduling have become valuable data sources. Detailed real-time information on PV and WT output levels, load profiles, tariffs, performance and component failures in the system allows the NSIIS operator to better plan and operate the system. These data have a positive effect on system maintenance and improve system stability. With the application of the NSIIS network scheduling strategy, the Xi'an to Urumqi section of the Lianhuo Expressway can attain a corresponding increase in CO<sub>2</sub> emission reduction and new energy penetration. Moreover, other pollutants can be reduced accordingly, thus meeting the expectation of environmental constraints.

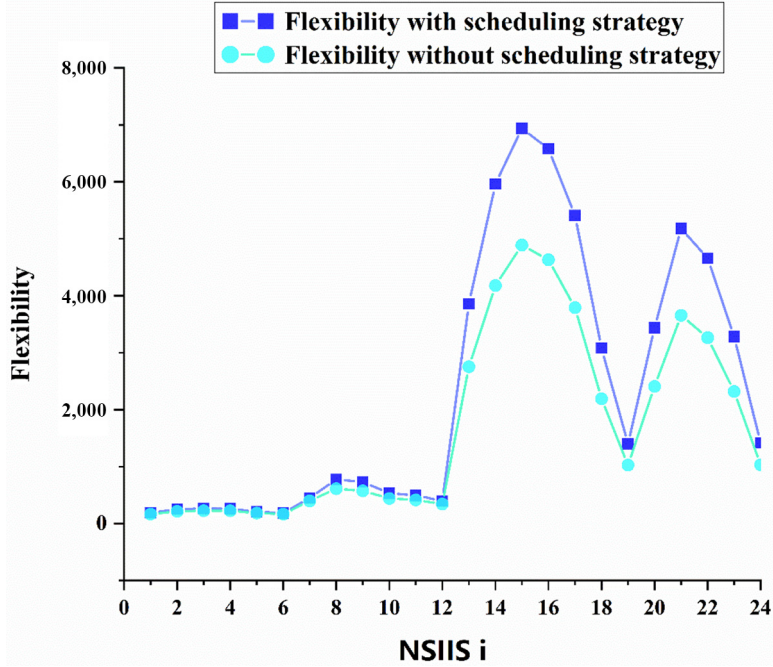
*4.2.2 Flexibility index.* Based on the definition of flexibility, the change in flexibility before and after the application of the NSIIS network scheduling strategy to the Lianhuo Expressway is calculated, as shown in Figure 4. Additionally, Figure 5 shows that the flexibility of each NSIIS increases to different degrees after applying the scheduling strategy of the NSIIS network. Figure 4 shows the growth rate of the flexibility of the Lianhuo Expressway microgrid cluster and the NSIIS after the application of the scheduling strategy.

The application of the NSIIS network scheduling strategy improves the flexibility index of the Lianhuo Expressway microgrid cluster and corresponding NSIIS. The flexibility of the entire microgrid system is improved by 29.17%, which greatly enhances the ability of the HPWIS to withstand changes and uncertainties in terms of PV and WT output levels and highway loads.

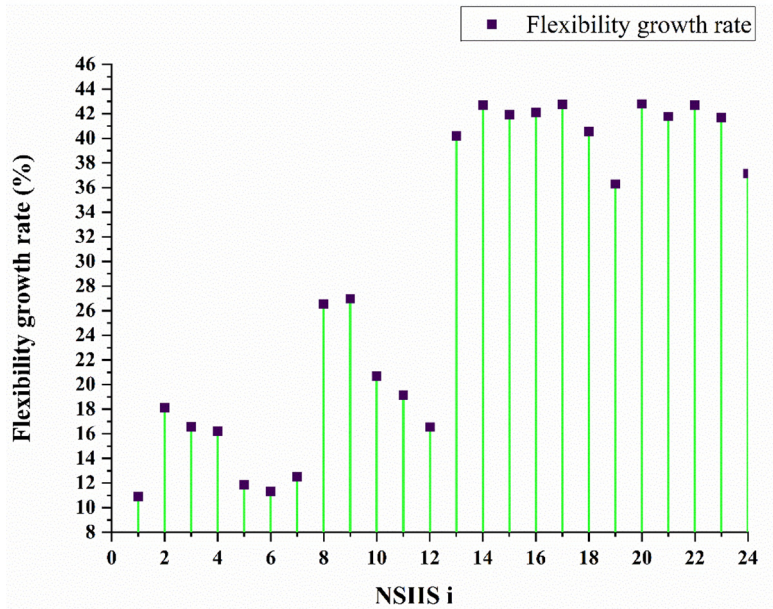
## 5. Summary and outlook

This paper analyzes the characteristics of electrical energy sources, grid characteristics, load characteristics and storage attributes attributed to the integration of PV and WT complementary power-generation systems with highways. From the perspective of highway and energy system adjustment, China is divided into 12 scenarios corresponding to different evolutionary models of the HESS according to the characteristics of the Chinese grid and charging pile, roads and solar-wind resource networks. To establish and optimally dispatch a new type of road traffic information system, it is necessary to combine PV and WT resources in roadside areas, and the distribution characteristics of both charging piles and highway loads should be

**Figure 4.**  
Flexibility  
comparison before  
and after applying  
the scheduling  
strategy to the  
Lianhuo high-speed  
NSIIS



**Figure 5.**  
Percentage of  
flexibility growth  
after the application  
of the NSIIS in the  
Lianhuo Expressway





considered during the construction of the Chinese backbone grid. According to natural resource, grid and load conditions, we adopt a three-in-one PV-WT highway integrated network. This study proposes a new model through which to capture the evolution of HESSs, which provides highway transportation vehicles and service facilities with a clean electricity supply and achieves energy transfer aided by an energy storage system, thus forming a new model of a transportation energy system with source-grid-load-storage-charge synergy. An evaluation method is proposed to improve the air quality index through the coordination of new energy generation and environmental conditions, and dynamic configuration and dispatch are achieved with a master-slave game model. Finally, choosing the Lianhuo Expressway as an example, the power-generation potential of PVs and WTs considering pollutant emission reduction for CO<sub>2</sub> emission reduction and system flexibility are calculated. The results indicate that compared with no application of the scheduling policy, the application of the NSIIS network scheduling method can give full play to the potential of wind power generation, at 31,679,811,815 kWh. Carbon dioxide emissions can be reduced by 31,584,772 tons because the installation of new energy-generation facilities facilitates vegetation restoration, and consequently, emissions can be reduced by 6,229,354 tons. Other emissions, such as carbon dust, sulfur dioxide and nitrogen oxide emissions, can be reduced by 8,616,909, 950,394 and 475,197 tons, respectively, and the system flexibility can be improved by 29.17%, which enhances the new energy-highway integrated network and can be adapted to the impact of large power fluctuations in the power-generation system.

In the period of the 14th Five-Year Plan, new energy will optimize the layout to promote large-scale development, develop energy storage to promote highly proportional consumption, continue to enhance innovation and research and establish a market-determined electricity price mechanism to provide the main support for achieving the goal of carbon peak and carbon neutrality (Xiaoning *et al.*, 2022). The three-in-one integrated network of PV and WT highways can provide an efficient solution to the “double-carbon” target laid out in the 14th Five-Year Plan.

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