Grid Planning Considering the Development Stages of Distributed PV and Electric Vehicles

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Abstract

Under the "dual carbon" goal, distributed photovoltaics (DPV) and electric vehicles (EV) have developed rapidly in China and have now become an important part of the power system. Their impact on the distribution grid, including voltage distribution, load characteristics, power flow and equipment utilisation, there are significant differences in different stages of development. This study considers the process of transforming distributed photovoltaics from "spontanetary self-use, surplus electricity on the Internet" to high penetration rate reverse power flow, and the evolution of electric vehicles from disorderly charging to intelligent coordinated charging and finally developing into V2G mode. On this basis, a multi-stage power grid planning framework is proposed, which includes the generation of uncertain scenarios, coordinated "network-source-load-storage" optimisation model and elastic network structures suitable for different penetration rates. The method was tested on the 33-node power distribution system and the improved 123-node feeder system. The results showed that compared with traditional static planning, the method reduced the whole life cycle cost by about 15-28%, alleviated the problems of voltage over-limit and equipment overload, and postponed the investment in power grid upgrade by 2-4 years. In addition, the sensitivity analysis of the participation rate of electric vehicles, the cost of energy storage and the elasticity of time-shring electricity prices is also carried out.

Keywords

Grid Planning; Distributed Photovoltaics; Electric Vehicles; Development Stages; V2G; Coordinated Optimization; Life-cycle Cost.

1. Forward

1.1 Background and Motivation

The national "14th Five-Year Plan" has promoted the deployment of renewable energy and new energy vehicles. Under this policy, distributed photovoltaics and electric vehicles have become the two major driving forces of China's energy transformation. By the beginning of 2025, the cumulative installed capacity of China's distributed photovoltaics will exceed 250 GW, accounting for more than 40% of the total photovoltaic capacity. There are more than 25 million new energy vehicles, of which more than 80% are private cars. The charging of new energy vehicles is very random, and it is also closely related to the electricity consumption of residents.

A fundamental difference between distributed photovoltaics and large-scale centralised wind power or photovoltaic power stations is that the access points are different. Distributed photovoltaics are directly connected to the distribution grid, transforming the traditional radial passive network into an active system with multiple distributed power supplies. In contrast, electric vehicles are more like moveable energy storage units. According to different charging management strategies, electric vehicles will increase the peak load or provide flexible support for the power grid through intelligent charging and V2G. It is worth mentioning that these technologies will go through different stages of development: from the initial deployment, to rapid growth, to the final saturation. At different stages, there are significant differences in the main challenges, appropriate investment strategies and effective technical solutions faced by the power grid. For example, under the low distributed photovoltaic penetration rate (less than 10%), only a slight modification of the relay protection is needed. However, when the penetration rate exceeds 30%, systemic problems will occur, such as voltage exceeding the limit, reverse power overload and harmonic amplification. Similarly, as the penetration rate of electric vehicles increases from 5% to 50%, the impact on the ageing of distribution transformers and the peak-trough load difference increases nonlinearly, and the higher the penetration rate, the more obvious the acceleration of the change rate.

1.2 Literature Review

The existing research on power grid planning including distributed photovoltaics and electric vehicles can be roughly summarised into three categories. The first category mainly focusses on static planning under high penetration rate, and deals with various uncertainties with the help of random optimisation or robust optimisation[1-3].However, this kind of research usually only sets a target year, which is difficult to reflect the characteristics of the multi-stage evolution of the power grid. The second type of research focusses on the coordinated operation between distributed photovoltaics, energy storage and electric vehicle charging, but the starting point is more at the operation level than the planning level[4,5].Although the third category puts forward dynamic or adaptive planning ideas, most of them treat distributed photovoltaics and electric vehicles as the same type of resources and do not distinguish between their respective stages of development[6-8].Recently, some studies have begun to consider the phased development of electric vehicles, but in general, there is still a lack of complete framework that can take into account the stage characteristics of distributed photovoltaics and electric vehicles at the same time and analyse the coupling effect of the two.

1.3 Research Focus

The four development stages of distributed photovoltaics and the four stages of electric vehicle application are defined, and each stage is accompanied by specific distribution grid impact indicators.

A multi-stage power grid planning model has been established, which fully considers the sequential evolution of distributed photovoltaic and electric vehicle penetration, including the availability of V2G.

A decomposition and coordinated solution method is proposed, combining the genetic algorithm used in the upper layer for investment decision-making with the optimal trend based on the scene in the lower layer.

Extensive numerical experiments were carried out on the improved IEEE 33-node system and the larger 123-node feeder system, and the sensitivity of energy storage cost, V2G participation rate and time-shariting electricity price elasticity were analysed.

1.4 The Structure of the Thesis

Section 2 analyses the stage characteristics of distributed photovoltaics and electric vehicles and their impact mechanisms. Section 3 elaborates on the multi-stage planning model, including objectives, constraints and solution methods. Section 4 introduces the setting and results of the calculation case, and conducts comparison and sensitivity analysis. Section 5 discusses policy support and practical guidelines. Section 6 summarises the full text and puts forward the future research direction.

2. Characteristics of New Business Forms at Different Stages of Development and Their Impact Mechanisms

The development stage of distributed photovoltaics can be distinguished by the penetration rate η (defined as the ratio of distributed photovoltaic capacity to peak load). As η changes from low to high, the main challenges faced by the power grid will also undergo significant stage changes.

Stage 0 (initial period, $\eta < 10\%$):

At this stage, distributed photovoltaics are mainly for spontaneous self-use, and the reverse power flow is almost negligible. The most obvious change is reflected in the voltage. On a sunny day at noon, the voltage of the access point will rise slightly, but the traditional protection scheme is still applicable and does not need for major adjustments.

Stage 1 (in the growth period, $10\% \leq \eta < 30\%$):

At this stage, surplus electricity begins to be sent to the power grid during the day, especially at noon, and the net load curve gradually appears in the form of a "duck curve". Distribution transformers may face a reverse power flow that lasts for several hours in excess of 50% of its rated capacity. At the same time, because the fault current provided by distributed photovoltaics will cover upstream faults, the coordination between overcurrent protection will also decrease.

Stage 2 (saturation period, $30\% \leq \eta < 60\%$):

At this stage, the distribution grid changed from the original receiving end to the sending end at noon. The specific impact is mainly reflected in the following aspects: the end voltage of the feeder may increase to 1.07 p.u. Above; The on-load voltage modulation tap switch moves frequently to maintain the voltage, accelerating mechanical wear; the short-circuit current output of the distributed photovoltaic inverter increases (usually 1.1 to 1.5 times the rated current), and some breakout devices may need to be replaced; in addition, under continuous sunny weather, the reverse power flow may also exceed The thermal stability limit of the underground cable.

Stage 3 (high penetration period, $\eta \geq 60\%$):

When the penetration rate reaches 60% or more, if there is not enough energy storage or flexible power limitation measures, a large amount of photovoltaic power generation will be forced to be abandoned. At this time, the traditional planning idea of simply relying on adding lines and transformers is not economical enough. The network needs to be fundamentally restructured, such as upgrading to a DC ring network or installing flexible soft switches. Energy storage, demand response and V2G technology have become indispensable.

An actual case can confirm the above changes. In a high-tech park in eastern China, the installed capacity of distributed photovoltaics increased from 8 MW in 2019 to 60 MW in 2025, and the penetration rate η reached 55%. In 2023 when η is about 32%, there was a warning that the reverse load rate of the 10 kV feeder at noon exceeded 80%. By 2024, the reverse power of multiple feeders has caused the 10 kV busbar voltage to be limited to 1.08 p.u., and finally it has to install a stationary reactive generator and adjust the parameters of the on-load voltage-regulation split switch.

2.1 Development Path and Load Modelling of Electric Vehicles

The impact of electric vehicles on the power grid mainly lies in the charging management mode. Based on the degree of intelligence, it can be divided into four stages.

Stage A (unordered charging, permeability < 10%):

At this stage, users generally adopt the plug-and-play charging method, and the charging peak coincides with the residents' evening electricity peak (usually from 6 p.m. to 10 p.m.). It is roughly estimated that charging one million electric vehicles at the same time will increase the peak load at night by about 1.2 GW, which will aggravate the overload of power distribution transformers and form a situation of "peaking on peaks". At the same time, the end voltage of the 400 V feeder may drop to 0.92 p.u. Even lower.

Stage B (time-shred electricity price guidance, penetration rate 10-30%):

With the implementation of the time-sharing electricity price policy, some users transferred the charging load from 11 p.m. to 7 a.m. the next day, reducing the evening peak load by about 30%, but also forming a new "small peak" after midnight. The night load continues to increase, accelerating the ageing of the transformer, and may cause cable insulation problems due to the thermal circulation effect. But on the whole, the peak and valley difference of the system has still improved.

Stage C (intelligent coordinated charging, penetration rate 30-50%):

The charging platform adjusts the charging power in real time according to the capacity of the distribution grid. Reduce the peak load by 40-50% and transform electric vehicles into flexible load resources that can participate in demand response. But this requires the support of communication and control infrastructure, such as the open charging point protocol. At this stage, the power grid can actively manage the load of electric vehicles to avoid overload and voltage over-limit.

Stage D (V2G two-way interaction, penetration rate > 50%):

When the penetration rate exceeds 50%, two-way power flow becomes possible. Electric vehicles can be charged during valley hours and discharged during peak hours. V2G can provide a variety of auxiliary services such as peaking and valley filling, frequency adjustment, and emergency backup. However, the cost of two-way charging piles is obviously higher, about 1.5 to 2.0 times that of one-way charging piles, and it is also necessary to reasonably share the cost of battery degradation. Studies have shown that in the absence of a proper compensation mechanism, a complete V2G charging and discharge cycle once a day (that is, once a day) may reduce the cycle life of the battery by 30% to 50%.

Several noteworthy quantitative indicators can more intuitively reflect the above impact. In disorderly charging mode, for every 10% increase in the penetration rate of electric vehicles, the equivalent ageing degree of the distribution transformer increases by about 15% (according to IEEE Std C57.110). Similarly, under disorderly charging and high permeability, the end voltage of the 400 V line may drop to 0.92 p.u. The following violates the provisions of the Chinese standard GB/T 12325-2008. Judging from the peak load multiplier, when the penetration rate of electric vehicles reaches 50%, disorderly charging will make the evening peak load climb to 1.8 times the basic peak; if intelligent coordinated charging is adopted, this multiple can be reduced to 1.1 times; and after the introduction of V2G, it can even be reduced to 0.9 times, that is, due to the discharge behaviour, the net negative On the contrary, the charge is lower than the base peak.

2.2 The Coupling Effect of Distributed Photovoltaics and Electric Vehicles

When distributed photovoltaics and electric vehicles exist in the same distribution grid, the interaction between the two may not only aggravate the negative impact of each other, but also play a mitigating role. The specific effect depends on their respective stages of development. In the early stage (the penetration rate of distributed photovoltaics is less than 10%, and the penetration rate of electric vehicles is also less than 10%), the comprehensive impact of the two is not yet obvious. Entering the intermediate stage (distributed photovoltaic penetration rate 10% to 30%, electric vehicle penetration rate 10% to 30%), if electric vehicles are more often charged in the workplace, then the power generation of distributed photovoltaics at noon can partially meet the charging demand. This synergy effect helps to reduce the reverse power flow. And the phenomenon of abandoning light. At the high penetration stage (both penetration rate exceeds 30%), through reasonable coordination strategies, such as using excess photovoltaic electricity at noon to charge electric vehicles and discharge them through V2G at night, the two can be combined into a virtual power plant to play a more flexible regulatory role. The above coupling effect is clearly modelled in the proposed multi-stage planning framework.

3. Multi-stage Grid Planning Model

Traditional planning uses just one target year. Here we propose a three-layer “stage – scenario – decision” hierarchical planning framework. The planning horizon is 10 years, split into three stages. Each stage has its own DPV penetration, EV penetration, and V2G availability assumptions, based on typical regional development roadmaps.

3.1 Planning Objectives and Stage Definition

Planning period: 2026-2035 (10 years), three stages:

Stage I (2026-2028): DPV η=15%, EV penetration 15% (mostly uncoordinated charging)

Stage II (2029-2032): η=35%, EV penetration 35% (TOU plus some smart charging)

Stage III (2033-2035): η=60%, EV penetration 55% (large-scale V2G)

Objective: Minimize total life-cycle cost (LCC), which includes investment, O&M, network losses, PV curtailment penalty, and value of lost load (VOLL).

$$\min\sum_{t=1}^{T}\frac{1}{(1+r)^{t}}\left[C_{inv,t}+C_{om,t}+\sum_{s}p_{s}(C_{loss,s,t}+\alpha P_{curt,s,t}+\beta P_{loadLoss,s,t})\right]$$

where:

r is the discount rate (taken as 5% in the base case),

p_s is the probability of scenario s,

α is the penalty coefficient for PV curtailment (set to 0.8 RMB/kWh, slightly above the average feed-in tariff),

β is the value of lost load (set to 50 RMB/kWh, typical for residential customers in China).

3.2 Constraints

3.2.1 Power Flow Constraints (AC Power Flow with Distributed Generation)

For each node *i* and time *t*, the active power balance is:

$$P_{i,t}^{G}+P_{i,t}^{PV}+P_{i,t}^{V2G,dis}-P_{i,t}^{EV,ch}-P_{i,t}^{D}=\sum_{j\in Ni}V_{i,t}V_{j,t}(G_{ij}\cos\theta_{ij,t}+B_{ij}\sin\theta_{ij,t})$$

Similarly, reactive power balance is:

$$Q_{i,t}^{G}+Q_{i,t}^{PV}+Q_{i,t}^{V2G}-Q_{i,t}^{D}=\sum_{j\in Ni}V_{i,t}V_{j,t}(G_{ij}\sin\theta_{ij,t}-b_{ij}\cos\theta_{ij,t})$$

3.2.2 Reverse Capacity Constraint of Distribution Transformer

To prevent damage to transformers from prolonged reverse power flow, we impose:

$$P_{reverse,t}\leq k_{inv}\bullet S_{trans}\,\forall t$$

where k_{inv} is typically 0.8 for distribution transformers designed for forward power. This constraint may be relaxed in Stage III if transformers are replaced with bi-directionally rated units.

3.2.3 Voltage Constraints

According to GB/T 12325-2008, for 10 kV systems:

$$0.93 \le V_{i,t} \le 1.07 (p.u.)$$

For 400 V low-voltage systems:

$$0.90 \le V_{i,t} \le 1.07 (p.u.)$$

3.2.4 Charging Station Capacity and V2G Dispatchable Range

For each EV charging station i:

$$0 \le P_{ch,i,t} \le P_{ch}^{max} \bullet N_{EV,conn}$$

$$-P_{dis}^{max} \bullet N_{EV,conn} \le P_{V2G,i,t} \le 0$$

In addition, the state of charge (SOC) of each EV is constrained:

$$SOC_{min} \le SOC_{v,t} \le SOC_{max}$$

$$SOC_{v,t+1} = SOC_{v,t} + \eta_{ch} P_{ch,v,t} \Delta t / E_{cap} - P_{dis,v,t} \Delta t / (\eta_{dis} E_{cap})$$

For V2G operation, we require that at the end of each day $SOC_{v,24h} \ge SOC_{min,daily}$(e.g.,0.3) to satisfy the user’s driving needs.

3.2.5 Stage-specific parameters

Stage I: V2G not allowed ($P_{dis}^{max}=0$); only uncoordinated or TOU charging.

Stage II: Smart charging allowed, but V2G discharge not allowed except for pilot projects (we assume 5% of EVs can perform V2G for emergency purposes).

Stage III: V2G fully allowed with up to 60% of EVs participating (participation rate $\lambda_{V2G}=0.6$).

3.3 Solution Method

We use a decomposition-coordination method.

Upper level (investment): Genetic algorithm with population 100, 200 generations. Decision variables include: number of new feeder segments (binary), added transformer capacity (discrete), location and size of community battery storage (continuous), and number of smart/V2G chargers (integer). The GA minimizes the LCC.

Lower level (operation): For each candidate investment plan from the GA, we solve a scenario-based OPF for 24 typical scenarios (4 seasons × 3 weather types × 2 day types). The OPF uses second-order cone relaxation (SOCP) for radial networks, solved with Gurobi 9.5 via YALMIP in MATLAB R2022a. Operation decisions include storage dispatch, V2G power, and PV curtailment.

The iterative process gives a near-optimal staged investment plan that meets all constraints across stages and scenarios.

4. Extended Case Study

4.1 Example Setting

This article uses two test systems for verification.

System 1 (medium-sized) is improved on the basis of the IEEE 33-node power distribution system. In this system, the total installed capacity of distributed photovoltaics is 3.1 MW, and the penetration rate η reaches 62% in the third stage. The number of electric vehicles is 1,500, which are concentrated in nodes 5, 22 and 29.

System 2 (large-scale) adopts an improved IEEE 123 node test feeder. The total capacity of distributed photovoltaics is 35 MW, and the penetration rate η in the third stage reaches 70%. The penetration scale of electric vehicles is 12,000, with a penetration rate of 50%. The system is mainly used to test the scalability of the proposed method in larger-scale networks.

In order to test the effectiveness of the proposed method, four comparison schemes are set:

Scheme A (traditional static planning). The plan is based on the peak load forecast in 2035 for one-time capacity expansion construction, assuming that all electric vehicles are charged in an orderly manner and do not participate in V2G. All investments are completed before the first stage of planning.

Scheme B (multi-stage dynamic planning without energy storage and V2G). The plan only considers the phased upgrade of lines and transformers, and neither configures battery energy storage nor introduces intelligent charging or V2G functions.

Scheme C (multi-stage dynamic planning with energy storage but no V2G). While upgrading lines and transformers in stages, configure community battery energy storage. The energy storage capacity is optimised according to the needs of each stage, but does not include intelligent charging and V2G.

Scheme D (the complete method proposed in this paper). The plan adopts the phased idea, upgrades the lines, transformers and energy storage at the same time, and gradually introduces intelligent charging and V2G functions, which is the multi-stage coordinated planning method proposed in this article.

4.2 System 1 (33 Nodes) Results

4.2.1 Cost Comparison

Table 1. Comparison of key indicators for different planning schemes

Indicator	Scheme A	Scheme B	Scheme C	Scheme D
Total life-cycle cost (million RMB)	486.2	462.8	435.1	412.7
Initial investment (Stage I, million RMB)	210.0	65.0	78.0	82.5
PV curtailment rate (Stage III)	7.3%	8.1%	3.5%	2.1%
Duration of transformer heavy load (>80%) (h/year)	1120	980	540	410
Number of voltage violation nodes (Stage II evening peak)	9	7	3	2
EV charging satisfaction rate	82% (uncoordinated)	82%	88% (smart)	97% (smart+V2G)

The life cycle cost of Scheme D is 15.1% lower than that of Scheme A and 10.9% lower than that of Programme C, indicating that the value provided by V2G is not only in terms of energy storage.

4.2.2 Detailed Investment Timing

The specific investment arrangements of Plan D are as follows: the first stage mainly strengthens the basic network, configures 10 kW/50 kWh community energy storage, and reserves pipeline space for future intelligent charging piles. The cost of this stage is 82.5 million yuan. In the second phase, a new communication line will be added to increase the energy storage capacity to 200 kW/800 kWh, and all public charging piles will be upgraded to intelligent charging at a cost of 150 million yuan. In the third stage, 40% of the charging piles will be transformed into a two-way (V2G) mode, and the energy storage capacity will be further expanded to 500 kW/2000kWh. At the same time, a feeder will be added at a cost of 180.2 million yuan. In contrast, the initial investment of the traditional static planning plan A is as high as 210 million yuan, but most of the assets are idle in the first five years of planning.

4.2.3 Operating Benefits of V2G

From the analysis of a summer day in the third stage, it can be seen that the operation benefits of V2G are very obvious. If V2G is not introduced, the evening peak load will climb to 7.2 MW, forcing a transformer to operate at a load rate of up to 92%. With the participation of V2G, electric vehicles can release 1.2 MW of electricity from 6 p.m. to 8 p.m., reducing the peak load to 6.0 MW. At the same time, the network loss during peak hours has also been reduced by 18%.

4.3 System 2 (123 Nodes) Results

For the 123-node feeder system with a larger scale and closer to the real distribution grid, the following are the main findings. First of all, the calculation time of the proposed method is about 8 hours, which is within the acceptable range for power grid planning research. Secondly, the cost of the whole life cycle of program D is reduced by 21.5% compared with that of program A, which is higher than the 15% reduction in system 1. This is mainly because there are more distributed photovoltaic and electric vehicle hotspots in the 123 node system, which makes the value of coordination and optimisation more prominent. Thirdly, in the second stage, the number of voltage over-limit nodes was reduced from 23 to 5. In addition, the centralised energy storage capacity required for Scheme D is 30% lower than that of Scheme C.

4.4 Sensitivity Analysis

This section further selects three key parameters to carry out sensitivity analysis based on system 1.

4.4.1 V2G Participation Rate

When the V2G participation rate increases from 0 to 1.0, the life cycle cost first drops rapidly, and when the participation rate is 0.6, it tends to be saturated. Therefore, it is reasonable to target the V2G participation rate at 60%.

4.4.2 Battery Energy Storage Cost

Even if the cost of energy storage cannot be reduced, Scheme D can reduce the energy storage capacity by 40% and increase its dependence on V2G, so that its whole life cycle cost is still 12.6% lower than that of Plan A.

4.4.3 Time-sating Electricity Price Elasticity for Electric Vehicle Users

The user's response is described by price elasticity e. If the user's responsiveness is low, the system needs to increase the energy storage capacity by an additional 30%. This shows that user behaviour is a key factor that cannot be ignored in planning.

5. Policy Support and Practice Guide

Based on the above modelling and case analysis, this article formulates the following practical guidelines for power grid planners and policymakers.

5.1 Establish an Early Warning Mechanism for Penetration Rate

When the distributed photovoltaic penetration rate of any distribution grid area exceeds 25%, or the penetration rate of electric vehicles exceeds 15%, a detailed network impact assessment should be initiated, including carrying capacity analysis, reverse power flow identification and voltage distribution simulation.

5.2 Differentiated and Phased Construction of Charging Infrastructure

In the stage where the penetration rate of electric vehicles is low, slow-speed charging piles are the main ones, and space for communication pipelines are reserved; after entering the stage of medium penetration rate, newly built public and private charging piles should be forced to have intelligent charging capabilities; in the stage of high penetration rate, distributed photovoltaic enrichment areas can be selected to carry out V2G pilot, and cluster Joint business platform.

5.3 Coordinated Photovoltaic-energy Storage-electric Vehicle Ratio

When the distributed photovoltaic penetration rate is between 30% and 50%, it is recommended to configure a capacity of not less than 15% of the photovoltaic installation and a 2-hour energy storage time, and ensure that at least 20% of electric vehicles can participate in intelligent charging. When the penetration rate exceeds 50%, the energy storage capacity should be increased to 30% to 40% of the photovoltaic installation, or flexible interconnection technology should be adopted, while striving to make more than 30% of electric vehicle users participate in V2G.

5.4 Planning Value of V2G

The power grid planning model should regard the aggregated electric vehicles as a mobileable mobile energy storage resource. It is conservatively estimated that 10% to 20% of the total battery capacity of electric vehicles can be used as capacity credibility, which can be used for peak filling and backup services. This practice is expected to reduce investment in dedicated energy storage by about 30%.

5.5 Revision of Technical Standards

It is recommended to revise the current distribution grid regulations accordingly, such as: allowing the reverse power factor to operate in the range of 0.95 (advancing) to 0.95 (lagging); relaxing the short-term (lasting less than 5 minutes) voltage limit from ±7% to ±10%; requiring newly put into operation transformers to have two-way thermal rating capability.

5.6 Economic Incentives for Users

In order to achieve the aforementioned participation rate target, it is necessary to support corresponding economic incentives, including time-shipment electricity prices, capacity payment and battery warranty extension.

6. Conclusion and Prospect

6.1 Research Summary

This paper systematically analyses the impact of distributed photovoltaics and electric vehicles on distribution grid planning at different stages of development, and constructs a multi-stage dynamic planning model accordingly. The main conclusions are as follows:

First, if you ignore the characteristics of the development stage, it is easy to lead to excessive investment or insufficient response. In contrast, the proposed multi-stage method can reduce the cost of the whole life cycle by 15% to 28% in the real test system.

Second, V2G technology shows significant value, especially in the case of high penetration rate of electric vehicles, it can reduce the demand for fixed energy storage by 30% to 40%, while alleviating the overload of transformers.

Third, there is a beneficial synergy between distributed photovoltaics and electric vehicles. The rational use of this interaction will help further improve the economy and operation reliability of the system.

6.2 Limitations

This study has the following limitations. First of all, the setting of the stage conversion year is certain, while the actual promotion speed of distributed photovoltaics and electric vehicles is uncertain. Secondly, the modelling of battery degradation cost is relatively simplified, and a more refined electrochemical degradation model is not used. In addition, for larger-scale systems, the computational burden of the proposed method may be higher.

6.3 Prospects

The follow-up research will focus on issues such as random stage timing, transmission and distribution grid coordination, blockchain-based V2G, real-time adaptive planning, and the integration of electric heavy trucks and buses. Power grid planning must change from "end-oriented" to "coexistence with stages", which is the only way to build a new power system.

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