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Demand Response-Based Carbon Reduction and Guidance Technologies for Vehicle-to-Grid Integration

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Abstract. In promoting global transportation electrification, electric vehicle development intensifies grid regulation pressure while creating opportunities for new power systems. V2G technology, as a transportation-energy fusion hub, aggregates EV resources to respond to grid needs, showcasing potential in optimizing energy structure. This paper reviews V2G carbon reduction technologies from three perspectives. First, it explores V2G system planning, benefit assessment, and multi-energy integration strategies for top-level design. Second, it analyzes optimized dispatch strategies for V2G clusters considering grid stability, crucial for executing demand response. Finally, it examines V2G incentive strategies based on market mechanisms and user behavior, revealing engagement drivers. The review concludes coordinated policy frameworks combining infrastructure planning, AI-driven dispatch systems, and market incentives are essential for maximizing V2G decarbonization, promoting energy-transportation integration for sustainability.

Keywords: Vehicle-to-Grid, Electric Vehicle, Demand Response, Optimal Dispatch, Energy Conservation and Carbon Reduction

1. Introduction

Addressing climate change and achieving the "dual carbon" goals have become a global consensus, with low-carbon energy transition serving as the key pathway. The electrification of transportation is accelerating, where electric vehicles (EVs) as substitutes for conventional fuel vehicles are significantly reducing direct carbon emissions in the transport sector. Research indicates that EVs could reduce CO_2 emissions by 28% by 2030 [1]. However, uncoordinated charging behavior may coincide with traditional peak electricity demand, threatening grid stability and potentially increasing carbon emissions from the power system. Vehicle-to-Grid (V2G) technology transforms EVs into distributed mobile energy storage units, enabling bidirectional interaction with the grid. Studies show that aggregated V2G virtual power plants already outperform some traditional frequency regulation solutions in terms of response speed and flexibility [2]. Under demand response (DR) mechanisms, V2G can schedule EVs to charge during off-peak periods and discharge during peak hours, providing load balancing, peak shaving, and renewable energy fluctuation mitigation—demonstrating significant carbon reduction potential [3]. This paper reviews V2G-based carbon reduction technologies across three dimensions: (1) macro-level system planning and benefit assessment, (2) operational-level cluster optimization and control, and (3) micro-level incentive

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mechanisms and user behavior analysis. It aims to provide policymakers, grid operators, and researchers with a technical overview and research references to advance V2G's role in achieving the "dual carbon" goals.

2. Analysis of carbon emission reduction technologies in Vehicle-to-Grid (V2G) systems

2.1. V2G system planning and benefit assessment

In the transition of V2G technology from concept to large-scale application, macroscopic system planning and benefit assessment are paramount. These foundational steps critically determine both the technical feasibility and strategic positioning within future energy ecosystems. Recent studies have systematically demonstrated the macroscopic value of V2G by examining its comprehensive impact on the power grid, the coordinated planning of infrastructure, and its deep integration with various energy systems.

2.1.1. Impacts and benefits of V2G as a DR resource

In response to policy mandates, enterprises have developed two types of demand response programs: incentive-based (where users receive compensation for reducing peak consumption [4]) and price-based (which guide autonomous load adjustment through time-of-use pricing [5]). The large-scale grid-connected operation of V2G presents both opportunities and challenges for the power system. Although disorderly access can exacerbate peak-valley differences, causing problems such as voltage limit violations, increased network losses, and harmonic effects, it poses a significant threat to grid safety [6-8]. Howerver, if an orderly charging and discharging management plan based on demand response can be developed, V2G can be transformed into a high-quality resource to alleviate power grid pressure and enhance stability. Existing research has shown that under the demand response mechanism, V2G technology can not enables grid load balancing through peak reduction and off-peak energy absorption, but also provide high-value auxiliary services such as frequency regulation and backup, while improving the overall operational efficiency and reliability of the power grid [9,10], giving the system additional flexibility [11]. In addition, the implementation of V2G can significantly enhance the ability of the power grid to absorb renewable energy - charging during peak periods of wind and solar power generation, discharging to support the power grid when renewable energy output is insufficient, effectively stabilizing the intermittency of renewable energy, which has become one of its most important carbon reduction benefits [12].

2.1.2. Coordinated infrastructure planning

The large-scale application of V2G depends on supporting infrastructure. Traditional planning models that separate vehicle and charger deployment are inadequate for V2G requirements. Consequently, the coordinated planning of V2G charging/discharging stations and Active Distribution Networks (ADNs) has become a research focus. Wang et al. proposed a distribution network expansion planning model that considers multiple energy resources, including shared V2G charging stations, solar-based distributed generation, and battery energy storage systems [13]. Liu et al. developed a coordinated planning model for ADNs and V2G charging stations using a Mixed-Integer Linear Programming (MILP) approach, which accounted for the distinct V2G charging load characteristics in residential, commercial, and office areas. Tests on the IEEE 33-bus distribution system demonstrated that coordinated planning effectively reduces total system costs [14].

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2.1.3. Deep integration with multi-energy systems

In the context of developing a new-type power system dominated by renewable energy, V2G serves not only as a grid regulatory resource but also as a crucial component of integrated energy systems. Li et al. incorporated the power network into cross-regional hydrogen supply chain planning due to its advantages in long-distance, economical energy transmission [15]. Tao et al. established a coordinated planning model for electricity and transportation systems, achieving emission reductions in both systems through the use of hydrogen fuel cell vehicles. Other studies have focused on strengthening the role of DR in modern energy system planning [16]. Mansourlakouraj et al. developed a risk-aware voltage/VAR support model based on reinforcement learning for unbalanced distribution networks incorporating DR and conservation voltage reduction strategies [17]. Azimian determined the optimal DR response intensity for a multi-energy microgrid by regulating peak load to balance energy conservation and economic benefits [18]. Luo et al. considered the DR flexibility of transport hubs in their coordinated planning model [19], while Efstratiadi constructed a holistic energy management system integrating DR, PV generation, and energy storage [20]. Ali et al. explored the synergistic optimization of V2G with hydrogen energy systems and DR to maximize the hosting capacity for renewable energy. Their research found that combining the flexibility of EVs with the long-duration storage advantages of hydrogen can significantly enhance the resilience and economic efficiency of the entire energy system, offering a new pathway for deep decarbonization [21]. Such DR-based, cross-carrier energy planning extends the value of V2G from the power system alone to the broader energy internet.

2.2. Optimized dispatch of V2G clusters

Following macroscopic planning, the subsequent core task is to translate the theoretical potential of V2G clusters into tangible grid services through refined optimization, dispatch, and control. This is a critical step for the practical implementation of V2G technology. Research in this area focuses on developing algorithms that can execute DR instructions in a real-time, efficient, and intelligent manner to manage the uncertainty of EV behavior while satisfying multiple grid operational constraints and achieving objectives such as peak shaving, valley filling, and low-carbon economic operation.

2.2.1. Price-based demand response and optimal dispatch

Price-based demand response primarily guides user behavior through time-of-use pricing. Researchers employ genetic algorithms and other intelligent methods to optimize charging/discharging strategies for EV fleets, aiming to minimize load variance and reduce peak-valley differences. Fatih et al. achieved peak shaving in distribution grids via plug-in EV management [22]. Mahmud developed practical peak-shaving strategies combining home storage, V2G-capable EVs and PV systems [23]. Attou et al. effectively managed peak loads in grid-connected microgrids with PV and V2G stations using decision tree algorithms [24]. Majed et al. demonstrated that algorithm-optimized bidirectional charging significantly reduces load fluctuations compared to unidirectional charging [25]. These studies confirm price signals effectively guide EV fleets to charge during off-peak and discharge during peak periods, smoothing grid loads. Bin et al. further enhanced this approach by incorporating tiered carbon pricing into dispatch models, enabling simultaneous response to electricity and carbon prices for combined economic and low-carbon benefits [26].

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2.2.2. Incentive-based demand response and advanced control

Incentive-based DR is typically used to provide high-demand ancillary services, such as frequency regulation, where the grid issues direct control commands and provides corresponding compensation. Alfaveh et al. used deep reinforcement learning (DRL) to solve the control optimization problem of V2G in power grid frequency regulation. This strategy utilizes a Deep Deterministic Policy Gradient (DDPG) agent to make rapid, continuous, and precise charging/discharging decisions based on real-time grid frequency signals. Its model-free nature enables it to adapt well to dynamic changes in the power grid environment, thereby achieving excellent performance and redundancy [27]. The application of such advanced control algorithms enables V2G to participate in more advanced DR programs with faster response requirements.

2.2.3. Reliability and uncertainty handling in demand response

The reliability of demand response is a primary concern for grid operators. The availability of EVs, user travel needs, and charging durations are all subject to high uncertainty, posing challenges to reliable response. To address these uncertainties, researchers have introduced methods such as robust optimization and stochastic optimization. Ren et al. developed a distributed robust optimization (DRO) dispatch scheme based on moment information. This scheme can make optimal decisions under worst-case scenarios without complete knowledge of the probability distribution of random demand, ensuring the economic viability and reliability of charging stations in uncertain environments [28]. Shokouhmand employed stochastic optimization methods to schedule EV charging/discharging patterns to enhance the flexibility and efficiency of microgrids [29].

2.3. V2G user-side incentives and market design

Technical feasibility and economic incentives are the core drivers for the large-scale development of V2G. Even with the most advanced dispatch technologies, V2G will struggle to move from demonstration to widespread adoption without effective market mechanisms and a deep understanding of user behavior. Therefore, designing effective market mechanisms and incentive measures, accurately understanding user psychology and behavioral patterns, and establishing a fair benefit distribution system are key to transitioning demand response from a technically feasible concept to a commercially successful reality.

2.3.1. V2G demand response pricing based on market games

The V2G market constitutes a complex ecosystem involving multiple stakeholders (grid operators, aggregators, and end-users), making game theory particularly suitable for pricing mechanism analysis. Chen et al. constructed a Stackelberg game model between an aggregator and EV users. In this model, the aggregator first announces a V2G price, users then decide whether and how to respond based on their own benefits, and the aggregator adjusts the price based on user responses until an equilibrium is reached. This model can identify an optimal V2G price that balances the interests of all parties [30]. Ma et al. innovatively applied cooperative game theory within industrial and commercial enterprises. By optimizing the V2G compensation price offered by a company to its employees' EVs, they achieved a "win-win" situation of reducing the company's electricity costs while increasing employees' income, providing a model for V2G business design in specific scenarios [31]. For emergency demand response, Wang et al. developed a deadline-aware online auction mechanism to efficiently aggregate V2G resources through dynamic bidding [32].

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2.3.2. Data-driven modeling of user demand response behavior

To design attractive incentive mechanisms, it is essential to deeply understand user decision-making behavior. Modern research is shifting from traditional macroscopic statistical models to fine-grained, individualized modeling based on big data. Zhang et al [33]. utilized massive vehicle GPS trajectory data combined with a dynamic energy consumption model to accurately reconstruct users' complete travel chains and real-time state-of-charge (SOC) variations. More importantly, they introduced Prospect Theory from behavioral economics to build a V2G participation decision model. This model not only quantifies objective factors like economic returns and battery degradation but also incorporates subjective psychological factors such as users' risk preferences, loss aversion, social status, and environmental awareness. This allows for a more realistic prediction of user response probabilities when faced with different V2G incentive schemes. Such data-driven, in-depth behavioral modeling enables the creation of "user profiles" and the design of personalized, precise demand response incentives.

3. Conclusion

This paper has systematically reviewed the research on demand response-based guidance technologies for large-scale V2G integration aimed at carbon reduction. The analysis reveals that fully realizing V2G’s decarbonization potential requires a multi-level coordinated framework integrating macro-scale system planning, operational-level intelligent dispatch, and user-centric incentive mechanisms. These three interconnected levels are crucial for advancing V2G technology from theory to practice.

However, the large-scale application of V2G still faces challenges. Future research should prioritize several key areas: first, developing more accurate battery health assessment models and integrating them into dispatch and pricing strategies; second, leveraging artificial intelligence and other technologies to deepen the understanding and prediction of user behavior while protecting user privacy; and third, accelerating the unification of relevant technical standards and business models, and strengthening the linkage of V2G with electricity and carbon markets.

In summary, through synergistic innovation at the technological, market, and policy levels, V2G technology is poised to evolve from a grid regulation tool into a key enabler for achieving "dual carbon" goals and building a clean, efficient, and integrated energy-transportation system.

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