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Review of Optimal Scheduling for Integrated Energy Systems Under New Demand Response Framework

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Abstract. Under the large-scale integration of electric vehicles (EVs), integrated energy systems (IES) face new challenges in dispatch optimization. This review examines advancements in IES optimization considering EV charging/discharging demands, including: on the supply side, establishing a multi-energy complementary framework by coupling electric boilers, organic Rankine cycles, and thermal storage systems to enhance the flexibility of combined heat and power units; on the demand side, coordinating price/incentive-based demand response with vehicle-to-grid (V2G) technology to achieve spatiotemporal load shifting for mitigating renewable energy fluctuations and peak-valley differences. The study proposes carbon trading mechanisms and bi-level dispatch models to reconcile economic, low-carbon, and stability objectives. Results indicate that coordinated supply-demand optimization and EV potential exploitation are key to efficiency improvement. Yet, breakthroughs are needed in cross-energy market mechanisms, dynamic battery health assessment, and distributed algorithms. Future work should integrate digital twin and AI technologies to establish electricity-gas-carbon coupled trading systems, promote the evolution of IES toward virtual power plant models, and support the development of new power systems.

Keywords: Integrated energy system, Coordinated charging/discharging of electric vehicles, Demand response, Carbon trading mechanism

1. Introduction

Driven by energy transition and carbon neutrality goals, Integrated Energy Systems (IES) have become a crucial solution for enhancing energy efficiency through their multi-energy complementarity and coordinated optimization capabilities [1]. The large-scale adoption of electric vehicles (EVs) has brought rapidly growing charging loads, presenting new challenges for IES optimal dispatch. In this context, research on IES optimization considering EV charging/discharging loads is critical for load fluctuation mitigation, renewable energy accommodation, and operational cost reduction, representing a key focus for smart grid and IES coordinated development.

Existing research has proposed a CCHP microgrid optimal dispatch model based on demand response and multi-energy complementarity, integrating wind/PV generation with gas turbine CCHP systems through comprehensive demand response [2]. The model addresses renewable uncertainty

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using typical scenario sets. Zhang et al. developed a two-stage coordinated optimization model for EV charging stations incorporating grid incentive mechanisms, pioneering the integration of dynamic peak-valley incentive policies with the objective of minimizing local grid load differences [3]. Their bi-level optimization framework achieved spatiotemporal coordination of diversified charging loads.

This paper reviews IES optimization approaches that incorporate coordinated EV charging/discharging strategies to maximize demand-side flexibility. Focusing on both IES supply-side and EV load-side coordination, we systematically examine supply-demand optimization under V2G interactions.

2. Overview of Integrated Energy System optimization

2.1. Integrated Energy System (IES)

An integrated energy system can be understood as achieving an efficient, clean, economical, and reliable energy supply through cascade utilization, comprehensive utilization, multi-energy complementarity, and interconnection of energy at the source side, grid side, and user side (load-storage). In essence, it pursues global multi-objective optimization of the energy supply process to the greatest extent possible (see Figure 1). Its key technologies lie in cascade utilization, adaptation to local conditions, multi-energy complementarity, and interconnection, ensuring high efficiency and rational energy use [4]. A typical IES realizes heterogeneous energy complementarity through electricity/heat/gas multi-energy networks to meet diversified user energy demands.

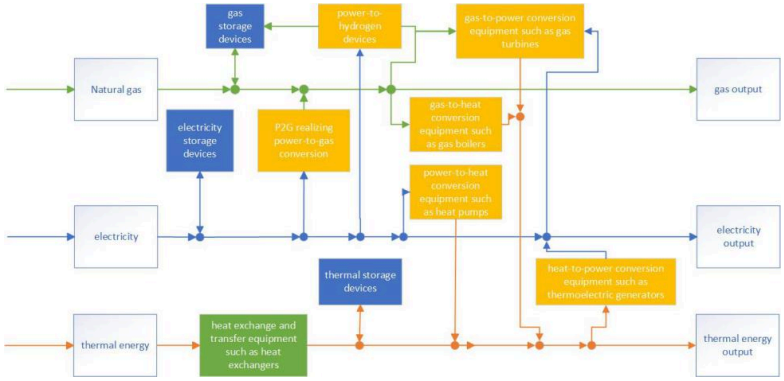

Figure1: Framework schematic diagram of integrated energy systems

During transmission in power grids, natural gas networks, and heating networks, IES generates electricity and heat through combined heat and power (CHP) units; connects power networks with natural gas networks via power-to-gas (P2G) technology; and implements electricity-to-heat conversion through equipment such as heat pumps (HP) and electric boilers (EB), thereby supplementing heat energy with electrical energy.

Combined cooling, heating and power (CCHP) is a multi-generation total energy system based on the concept of cascade energy utilization, integrating cooling, heating (space heating and domestic hot water supply) and power generation processes [5]. Its purpose is to improve energy efficiency and reduce carbon compounds and harmful gas emissions. Taking into account the multi-energy structure characteristics of the system and considering the coordination and interconnection between different energy forms, the energy flow and source-load structure within the microgrid are shown in Figure 2.

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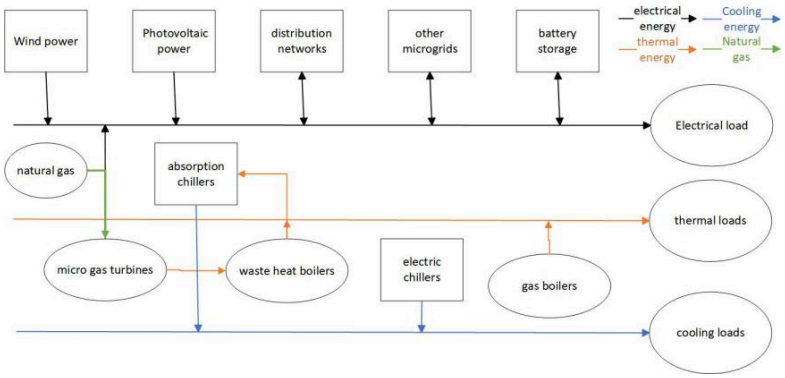

Figure 2: CCHP Microgrid Structure Diagram

2.2. Current research status of Integrated Energy System optimization dispatch

With the deepening of energy transition and the rapid development of multi-energy coupling systems, combined cooling, heating and power (CCHP) multi-microgrid systems have become important carriers for improving energy utilization efficiency due to their multi-energy complementarity characteristics. However, the uncertainty of renewable energy output, conflicts of interest among multiple entities, and the complexity of demand-side response mechanisms pose challenges to system optimization dispatch. In recent years, scholars worldwide have conducted research focusing on integrated demand response (IDR), multi-agent game theory, and uncertainty optimization, achieving a series of advances.

2.2.1. Integrated demand response and game-based optimization

To enhance the flexibility and efficiency of integrated energy systems (IES), recent research has focused on combining demand response (DR) strategies with game-theoretic approaches. Price-based DR mechanisms model user load behavior through elasticity matrices and optimize energy usage under time-of-use pricing. For example, Li et al. developed a Stackelberg game model between users and microgrids, which achieved lower user payments and higher operator profits by balancing grid constraints and consumer comfort [6]. Incentive-based DR further exploits the bi-directional nature of electric vehicles (EVs), aligning their charging and discharging patterns with system needs through optimized dynamic pricing and participation incentives [7].

In multi-agent environments, cooperative game models—such as those based on the Shapley value and Nash bargaining—have been applied to fairly allocate benefits while ensuring coordinated scheduling [7]. Other studies designed multi-microgrid transaction frameworks using hybrid game models that combine non-cooperative decision-making with internal and external electricity trading mechanisms. Simulation results showed that this approach improves individual microgrid performance and reduces peak loads on the distribution network [8].

2.2.2. Multi-energy coupling under uncertainty

To address renewable energy fluctuations and improve inter-network synergy, integrated electricity-gas systems have been widely studied. A typical approach involves bi-level optimization models where upper-layer scheduling coordinates natural gas dispatch and lower-layer decisions control wind curtailment and power-to-gas (P2G) operations. By transforming the bi-level structure into a

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solvable mixed-integer formulation using Karush-Kuhn-Tucker (KKT) conditions, these models can improve wind utilization and reduce system operating costs [9].

Such multi-energy coupling strategies significantly enhance the system's ability to manage uncertainty, especially in scenarios involving high renewable penetration. Coordinated scheduling of gas turbines, P2G units, and energy storage has become key to enabling low-carbon and resilient IES operations.

3. Overview of electric vehicle coordinated charging/discharging strategies

3.1. Coordinated charging/discharging

Coordinated charging refers to controlling charging behaviors using feasible technical means while meeting EV charging demands, thereby achieving peak shaving and valley filling of grid load to reduce load fluctuations, and ultimately realizing coordinated development between EVs and the grid to ensure safe and stable grid operation. The process is illustrated in Figure 3. Specific coordinated charging control methods are categorized into price-based control and power-based control [10].

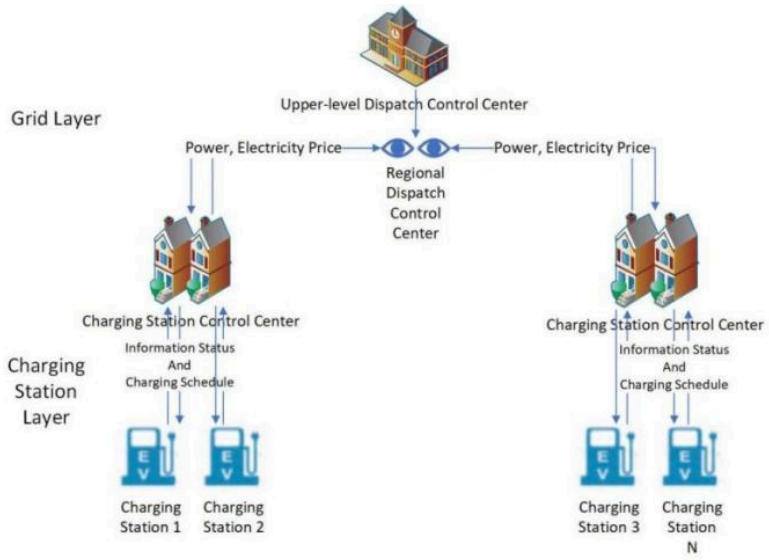

Figure 3: EV Coordinated Charging Flowchart

3.2. Vehicle to Grid (V2G)

EVs, as energy storage devices, can both draw power from the grid and transmit power back to the grid [11], giving rise to V2G (Vehicle-to-Grid) technology. Under the V2G framework, EVs possess dual characteristics as both sources and loads, along with the advantages of bidirectional communication and bidirectional power transfer [12]. This benefits both the grid side and the user side. V2G aims to mitigate the adverse effects of large-scale EV charging on the grid, such as voltage drops and load overloads, improving grid economics and renewable energy integration. Simultaneously, EV users can discharge power back to the grid to earn certain profits while meeting their own needs [13].

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3.3. Current research status of coordinated charging and discharging strategies for electric vehicles

Li and Xiao et al. analyzed the impact of large-scale EV charging on power grids and proposed a nonlinear optimization model based on load forecasting [14]. Through spatiotemporal analysis of charging curves and genetic algorithm-based scheduling, they reduced peak-valley differences by 23% while avoiding new peaks. However, the study noted limitations due to charger power constraints, calling for integrated peak-shaving strategies.

Further research introduced dynamic time-of-use pricing and demand response models. Monte Carlo simulations showed that with 40% user participation, transformer peaks dropped by 33% and operator profits rose 28% [10]. The study cautioned that tiered pricing may cause load clustering, suggesting smoother price mechanisms.

In bidirectional charging architectures, three-level Vienna rectifiers achieved 96% efficiency with <4% THD, while seven-level PFC topologies halved voltage stress using capacitor clamping. Wang Bo et al. modeled battery degradation based on temperature and DoD, showing 10°C or DoD increases (30%→80%) shortened battery life by 15% and 35% respectively [15][16]. They proposed price compensation strategies to reduce load fluctuation by 34% while limiting annual degradation to under 5%.

Coupled route planning and V2G models using improved genetic algorithms reduced costs by 19% and mileage by 15% in logistics networks [17], while optimizing transformer peak-valley ratios by 21%. Wang and Ai confirmed that setting economic and security weights at 0.6 and 0.4 respectively optimized multi-objective outcomes [15].

Challenges remain: real-time battery health is underutilized, routing lacks price-time coordination [17], and while SiC devices boost efficiency 3–5%, they cost 2.8× more than silicon [16]. Future directions include digital-twin-based virtual power plants, broader use of wide-bandgap devices with costs projected to drop to 1.5× silicon by 2025, and blockchain-enabled distributed trading, improving settlement efficiency by 40% [17]. These advances aim to reposition EVs as active grid resources.

4. Optimal scheduling of integrated energy systems considering electric vehicle charging/discharging under new demand response frameworks

Leveraging the complementary and cascaded characteristics of integrated energy systems (IES), and the dispatchable potential of EV loads, optimal scheduling strategies have emerged to mitigate renewable energy volatility and EV-induced peak-valley imbalances. Bilateral supply-demand response mechanisms combined with coordinated EV operations have proven effective for system optimization [18].

4.1. Flexibility and demand response in integrated energy systems

To address the challenges posed by large-scale integration of electric vehicles (EVs) and renewable energy, integrated energy systems (IES) must enhance both supply-side flexibility and demand-side responsiveness. On the supply side, traditional combined heat and power (CHP) systems often suffer from limited adjustability due to electric-thermal coupling. One study proposed coupling electric boilers (EB) with organic Rankine cycle (ORC) units, introducing the electric-thermal output ratio as a metric for operational flexibility. This approach expanded the CHP's adjustment range by 20–30%, effectively mitigating peak conflicts between electric and thermal loads [19]. In parallel,

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coordinated operation of gas turbines (GT) and thermal energy storage (TES) systems further improved supply flexibility by enabling complementary natural gas and electricity outputs [20].

On the demand side, demand response (DR) strategies play a crucial role in balancing loads through user participation. Price-based DR leverages time-of-use (TOU) electricity price elasticity matrices to model transferable and reducible loads. Wu et al. developed a compensation mechanism incorporating electric load transfer rates and thermal/cooling load substitution rates, achieving a ~15% reduction in peak-valley load differences while maintaining user comfort [19]. Incentive-based DR focuses on the dual "source-load" nature of EVs. By integrating dynamic TOU pricing with vehicle-to-grid (V2G) technology, EV cluster discharge power during peak periods increased by 30%, effectively smoothing out load fluctuations [21].

4.2. EV scheduling and multi-objective optimization

The coordinated scheduling of EV charging and discharging is critical to unlocking their full potential as flexible resources in IES. Based on travel survey data, Zhang et al. applied Latin hypercube sampling to construct probabilistic distributions for EV charging start times and driving distances. A charging/discharging model with state-of-charge (SOC) constraints was established, along with a dynamic pricing mechanism. Charging tariffs were raised during peak hours (e.g., ¥0.8/kWh) to suppress uncoordinated charging, and lowered during off-peak periods (e.g., ¥0.3/kWh) to encourage valley-filling behavior. This reduced peak-valley load differences by 21.5% [18][20]. Additionally, integrating reactive power compensation from energy storage systems reduced EV dispatch costs by 18% and active power losses in distribution networks by approximately 12% [21].

At the system level, multi-objective optimization models aim to balance cost-efficiency, emission reduction, and operational stability. One study introduced a tiered carbon pricing mechanism (base price μ = ¥50/t, increment rate σ = 10%) to quantify carbon trading costs, resulting in a 1.6-ton reduction in carbon emissions [19]. A bilevel optimization framework was also developed, with the upper level minimizing total system costs and emissions and the lower level coordinating EV scheduling, ultimately achieving 8.5% cost savings and 12% emission reduction [20]. Another study incorporated node voltage deviations and active power losses into the objective function, applying an improved genetic algorithm to reduce voltage deviations by 22.9% [21]. These integrated approaches demonstrate the synergistic benefits of coordinated EV management and carbon-aware optimization in modern energy systems.

5. Conclusion

Integrated Energy Systems (IES) have significantly improved energy utilization efficiency and economic low-carbon operation capabilities through coordinated optimization on both supply and demand sides and coordinated charging/discharging strategies for electric vehicles (V2G). Research shows that the introduction of electric boilers (EB) and organic Rankine cycle (ORC) equipment in CHP units on the supply side can expand the electric-thermal ratio adjustment range by 20%-30%, effectively solving the "peak overlapping" problem of electric and thermal loads. Meanwhile, on the demand side, based on dynamic time-of-use electricity pricing and incentive compensation mechanisms, combined with EV charging/discharging behavior prediction (such as Latin hypercube sampling fitting of travel data), the load peak-valley difference can be reduced by 15%-21.5%. Further research indicates that through collaborative optimization of a tiered carbon trading mechanism, carbon emissions can be reduced by 1.60-3.7 tons, verifying the effectiveness of multi-

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strategy coupling. Typical case analysis shows that EV participation in dispatching can not only reduce distribution transformer peak loads by 33% and distribution network active power losses by 12%, but also maintain total cost stability while increasing the renewable energy consumption rate to over 95%.

Although this study systematically reviews the coupling mechanism of supply-demand bilateral collaborative optimization and EV charging/discharging strategies, there are still areas for improvement. First, the scheduling model lacks sufficient verification of dynamic response in multi-time-scale coordination and fails to fully integrate real-time electricity prices with renewable energy fluctuation characteristics. Second, the dynamic modeling of battery health status and strategy coupling mechanism under V2G scenarios has not yet been achieved, which may constrain long-term applications. Future work should integrate digital twin technology for real-time battery life assessment and construct reinforcement learning frameworks to achieve dynamic coordination between second-level response and day-ahead optimization, thereby improving scheduling robustness.

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