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IoT-Enabled Optimal Incentive Strategy for Flexible Loads in Intelligent Demand Response Frameworks

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Dear Editor,

In response to the escalating global energy crisis, the world's energy supply is undergoing a rapid transition toward renewable and sustainable energy sources. Renewable energy sources, notably wind and solar power, have emerged as pivotal alternatives and are being integrated into large-scale practical applications. However, inherent challenges—such as intermittency, geographical constraints, and the temporal imbalance between supply and demand—introduce significant volatility, undermining the structural stability of the power grid and posing challenges to large-scale deployment. Demand-side flexibility is increasingly recognized as an essential mechanism for mitigating the imbalance between peak-load shortages and off-peak surpluses.

Simultaneously, rapid demand response plays a critical role in maintaining grid stability, while being deeply contingent upon end-user engagement. DR strategies are typically classified based on their underlying driving mechanisms into two primary categories: price-based and incentive-based programs.[1] In incentive-based schemes, users receive compensatory payments for responding to grid requirements according to established policies. These include direct load control (DLC), Emergency Demand response (EDR), and Ancillary Service Markets (ASM). The Price-based DR (PBDR) strategy leverages time-of-use (TOU) pricing to incentivize users to shift their consumption patterns. By responding to dynamic pricing signals, users can optimize their energy costs during specific periods. Common implementation programs include Time-of-Use (TOU) pricing and Real-Time Pricing (RTP).

However, demand response strategies may reduce thermal comfort in buildings. As people spend approximately 90% of their time indoors, indoor thermal comfort plays a crucial role in human health, well-being, and productivity.[2,3] In addition, in regulated markets such as China, price-based DR can exert disproportionate adverse effects on vulnerable demographics, including low-income households, infants, and the elderly. Low-income groups often compromise thermal comfort and physical health to mitigate rising energy costs, while the elderly face heightened mortality risks during extreme thermal events. Furthermore, infants exhibit extreme sensitivity to environmental fluctuations. Given these socio-economic disparities, incentive-based policies are increasingly regarded as a more equitable and viable alternative.[4] For both aggregators and end-users, the design of optimal incentive mechanisms remains a pivotal challenge. Establishing bidirectional communication between the distribution network and end users is essential for effective energy management. Recent advances in the Internet of Things (IoT) and artificial intelligence (AI) have made such interactions feasible, enabling automated systems to coordinate the entire demand response process, from decision-making to scheduling.[5]

Figure 1 presents an IoT-based smart demand response framework that operates across three interconnected layers: generation, retail, and consumer. At the generation layer, control signals are issued and allocated based on forecasts of renewable energy generation. At the retail layer, incentive policies and control strategies are formulated according to electricity prices, user participation, and load-shifting potential, determining parameters such as response duration, building type, and the number of participating buildings. At the consumer layer, the system predicts the future dynamics of indoor temperature, evaluates thermal comfort conditions, and estimates potential economic benefits.

Leveraging IoT infrastructure, the system enables real-time coordination between the power grid and end users. Demand response protocols are activated during periods of high renewable generation, supply shortages, or increased grid stress. The system quantifies the flexible load capacity across different building sectors, including residential, office, commercial, and hospitality buildings, and transmits this information to the aggregator. Upon receiving demand response signals, the aggregator dispatches localized instructions to users through mobile devices. Through an interactive interface, users can visualize projected indoor temperature trajectories and variations in Thermal Sensation Vote (TSV), allowing them to monitor potential changes in indoor conditions and make informed decisions regarding participation in demand response programs.

To support the large-scale integration of IoT infrastructure into future power grid systems, this paper provides a comprehensive review of recent developments in IoT-enabled smart demand response. Through technological and economic analyses, the study identifies key barriers to large-scale deployment and outlines potential pathways and strategies for future development.

RECENT ADVANCES IN IOT-DRIVEN DEMAND RESPONSE FOR SMART GRIDS

Architectural frameworks and enabling technologies for the internet of things

The IoT, as a key enabling technology for demand response, provides end-to-end support across the entire operational chain, including data acquisition, information processing, decision-making, and control. The conventional IoT architecture typically follows a three-layer structure comprising the perception layer, network layer, and application layer. Smart devices, such as smart sockets and smart meters, are responsible for collecting energy consumption data and executing control commands. The network layer utilizes communication protocols such as MQTT and CoAP to transmit data to the cloud. Although this architecture is simple and well established, the rapid growth in the number of buildings and connected devices involved in demand response, together with increasingly stringent requirements for real-time

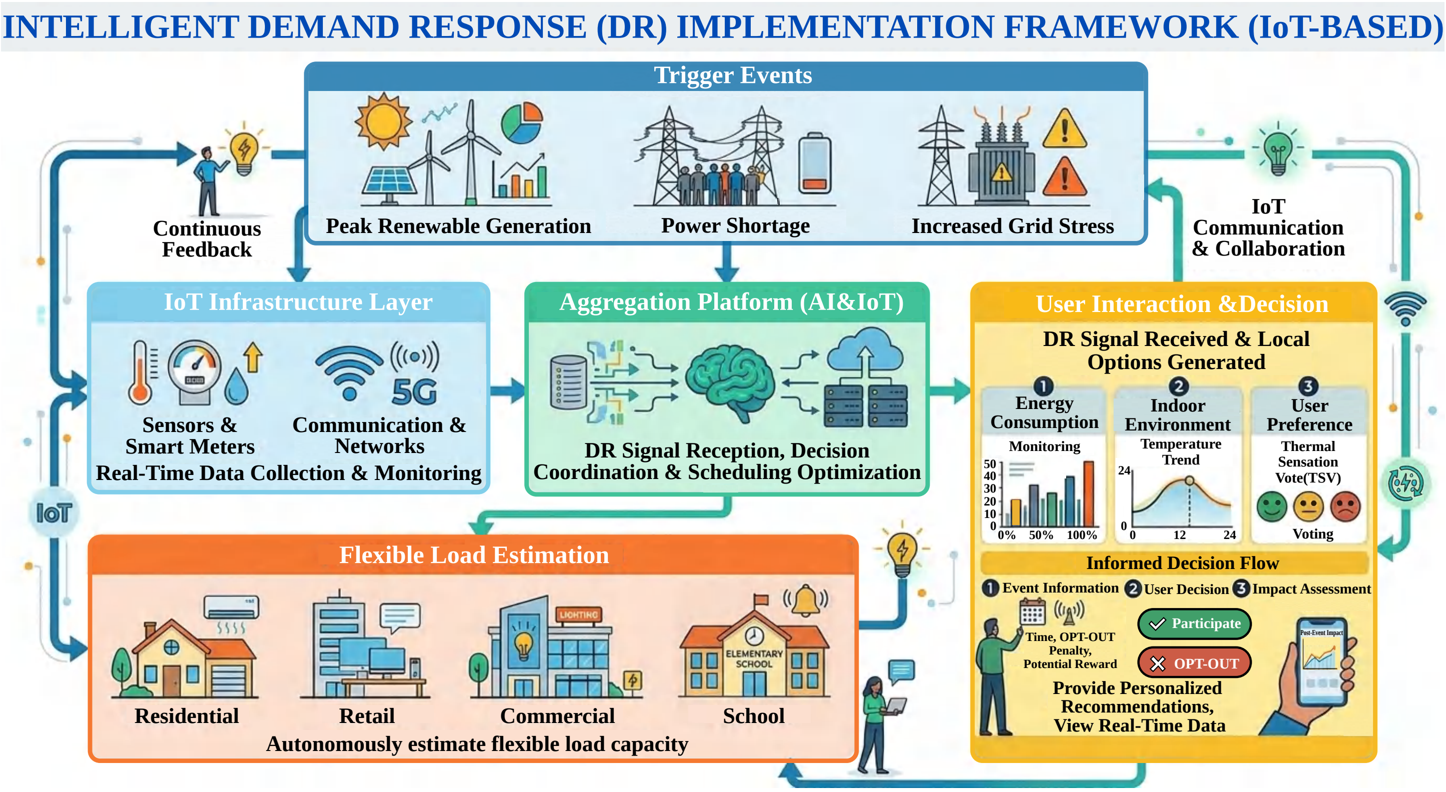

Figure 1. Intelligent Demand Response Frameworks.

feedback and control, exposes several limitations of centralized processing. These limitations include network bandwidth bottlenecks, increased communication latency, and reduced system scalability. Consequently, edge computing has been introduced into IoT systems. In this architecture, computing and storage resources are deployed at the network edge, close to users' gateways or access points. With the rapid development of artificial intelligence and big data technologies, multi-agent systems have been proposed as an effective approach for the distributed quantification and management of flexible resources. In this architecture, each agent, such as a microgrid controller, a home energy management system, or an electric vehicle charging station, is equipped with autonomous sensing, decision-making, and communication capabilities. Through cooperative interaction, these agents coordinate to achieve system-level energy optimization objectives, including supply–demand balancing in microgrids and participation in market-based demand response mechanisms. A stable and reliable communication network serves as the backbone connecting all layers of the IoT. Various communication technologies are typically employed in combination, including cellular IoT technologies (e.g., Narrowband IoT and 5G), local area network technologies (e.g., Wi-Fi and Zigbee), and low-power wide-area network technologies (e.g., LoRa). In terms of data management and processing, the IoT generates large volumes of heterogeneous data from multiple sources. A key challenge, therefore, lies in effectively managing this data and extracting actionable information from it. Cloud platforms and cloud computing technologies serve as the central hub of IoT systems, providing scalable capabilities for data storage, processing, and computation.

Classification and evolution of incentive strategies

In IoT-enabled DR systems, users act as the ultimate agents responsible for implementing DR actions. However, electricity consumption behavior is highly autonomous and often unpredictable. Without appropriate incentives, users typically lack the motivation to actively participate in DR programs. Therefore, designing effective incentive mechanisms that encourage voluntary adjustments in electricity consumption is critical for achieving DR objectives.

This section reviews the topic from three perspectives: the classification of incentive strategies, optimization objectives, and the integration of technology and user behavior. Traditional DR incentive mechanisms are generally divided into two categories: price-based DR and incentive-based DR. Under these schemes, system operators or load aggregators establish agreements with users either to directly control certain loads—such as air conditioners or water heaters—when necessary, or to request users to reduce their electricity consumption by a specified amount in exchange for financial compensation. Typical incentive-based DR programs include DLC and interruptible load. With the development of IoT technologies, prototype smart DLC systems have been implemented, enabling rapid responses to sudden grid load fluctuations and thereby reducing the duration and impact of power outages. As research progresses, the distinction between price-based and incentive-based strategies has gradually become less clear, leading to the emergence of hybrid approaches. For example, based on time-of-use pricing, additional reward points or discounts may be provided to users who actively participate in peak-shaving programs, forming a composite mechanism characterized by "price as the primary driver and incentives as supplementary measures".

The design of effective incentive mechanisms fundamentally relies on the accurate quantification of demand-side flexibility. Current research is progressively shifting from coarse estimation and rule-based regulation toward high-resolution quantification and fine-grained control, often requiring minute-level scheduling. At the same time, the scope of analysis is expanding from single-zone buildings to multi-zone systems and even urban-scale applications. Consequently, aggregation effects, market participation, and grid stability at the community and city levels have emerged as key research priorities.

The optimization goals of incentive strategies and modeling

On the consumer side, the primary objective is to minimize electricity costs while maintaining user comfort. Excessive or poorly scheduled DR actions may significantly affect the user experience; therefore, recent studies typically incorporate user comfort as an important constraint or optimisation objective. Current studies primarily rely on the temperature range method, adaptive models, and PMV-based approaches, including their modified versions, to evaluate dynamic thermal comfort. On the grid side, the objectives include reducing the peak-to-average power ratio to alleviate investment pressure on grid infrastructure; providing ancillary services, such as frequency regulation and voltage support, to ensure secure and stable grid operation; and promoting the local consumption of renewable energy in order to reduce wind and solar curtailment. To address these complex multi-objective optimization problems, researchers have developed a variety of mathematical models and intelligent optimization methods, including game-theoretic models, combinatorial optimization techniques, heuristic algorithms, and reinforcement learning approaches.

Personalized incentives

The deep integration of IoT technologies has enabled the design of incentive mechanisms to evolve from static, one-size-fits-all approaches toward dynamic, personalized, and real-time interactive models. Through IoT-enabled monitoring, users' electricity consumption behavior can be observed in real time. Mobile applications allow users to access their energy consumption data and estimated electricity bills at any time. This transparent feedback itself acts as an effective incentive, enhancing users' awareness of energy-saving opportunities and encouraging them to respond proactively to price signals.

By leveraging the large volumes of data collected through IoT systems, operators can construct user profiles that capture electricity consumption patterns, price sensitivity, and comfort preferences. Based on these profiles, differentiated incentive strategies can be designed for different user groups. For example, users with high flexible load potential may be offered higher-value incentive schemes to participate in DLC programs. For users prioritizing comfort, accurate real-time electricity pricing information can be provided to help them reduce electricity costs without compromising indoor comfort. Accurate load forecasting forms the foundation for effective incentive design. Using IoT data in combination with machine learning algorithms, researchers are able to estimate users' demand response potential during specific time periods with greater precision.

CHALLENGES IN IMPLEMENTING IOT-ENABLED DEMAND RESPONSE FOR SMART GRIDS

Despite the potential of IoT-driven operations, two primary challenges hinder the scalability of these technologies.[6] First, economic constraints arise from the high costs associated with acquiring real-time data across extensive building portfolios; as the density of rooms and devices increases, deployment expenses often become prohibitive. Second, privacy concerns present a significant social barrier, particularly in residential contexts where users may be hesitant to permit extensive sensor installations. Since the success of demand response initiatives is fundamentally contingent upon occupant participation, addressing these financial and privacy-related concerns is essential for widespread adoption. The integration of these communication technologies also introduces critical security vulnerabilities that must be mitigated. Cyberattacks targeting smart grid infrastructures can result in cascading failures, leading to widespread power outages and substantial financial losses for utilities and energy providers. Beyond structural damage, data breaches compromise sensitive consumer information, further exacerbating the privacy concerns that hinder occupant participation.

CONCLUSION

Demand response is widely regarded as a promising and economically viable strategy for mitigating renewable energy variability and improving the operational stability of electricity systems. However, demand response actions may compromise building service quality, particularly thermal comfort. This paper proposes a general framework for evaluating flexible resources and thermal comfort in power grid systems based on the IoT. It reviews the current state of research on IoT-enabled demand response strategies and examines the potential of IoT technologies for quantifying building flexible resources. In addition, the key challenges hindering the large-scale deployment of such approaches are identified. To further expand the implementation of demand response, a generalized tool for quantifying IoT-enabled flexible resources should be developed to facilitate broader participation in grid demand response programs.

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DECLARATION OF INTERESTS

The authors declare no competing interests.