論 文 内 容 の 要 旨

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論文題名	A Study on Distributed Energy Resource Management for Grid-interactive Efficient Buildings (グリッドインタラクティブ・エフィシェント・ビルディングに向けた分散型エネルギーリソースマネジメントに関する研究)

論文内容の要旨

The drive toward a low-carbon society and the urgent need to address energy issues have gained increasing prominence in recent years, as evidenced by the United Nations Sustainable Development Goals. This global shift underscores the critical necessity of transitioning to sustainable energy systems, particularly in the face of challenges such as climate change and energy scarcity. The adoption of renewable energy sources, notably solar and wind power, is playing a pivotal role in paving the way for this sustainable future. Data from the last few decades shows a consistent and impressive growth in the worldwide capacity of renewable energy installations. Despite their environmental benefits, renewable energy sources present significant challenges for the capacity and stability of electricity grids. Their output is inherently inconsistent and subject to fluctuations due to environmental factors like weather and wind speed, and lacks the controllability characteristic of traditional power stations. Such variability in renewable energy production can lead to substantial issues in grid stability, including frequency fluctuations, grid line overloads, and imbalances between supply and demand. To compensate for the unpredictability of renewable energy outputs, there is a growing need for measures such as adjusting generation levels and utilizing energy storage systems. These interventions are essential to ensure a reliable and efficient integration of renewable energy into the power system.

Addressing these challenges, grid-interactive efficient buildings (GEBs) have emerged as a key solution. Defining by the U.S. Department of Energy, GEBs are energy-efficient buildings that use smart technologies and on-site distributed energy resources (DERs) to provide demand flexibility. The international energy agency (IEA) also has a similar definition. They co-optimize for energy cost, grid services, and occupant needs and preferences in a continuous and integrated manner. GEBs are becoming pivotal in enhancing the affordability and reliability of power systems in the U.S., significantly contributing to the reduction of greenhouse gas emissions by reducing overall energy consumption and enhancing demand flexibility. This is crucial for the seamless integration of renewable energy sources into the grid. GEBs offer direct benefits to consumers, such as reduced system costs and enhanced demand flexibility, leading to lower electricity bills and reduced consumption. They also improve the reliability of the system and increase the satisfaction of building owners and occupants by providing more options, resilience, and flexibility in terms of electricity consumption. The multifaceted benefits of GEBs highlight their essential role in transforming the energy landscape and enhancing consumer experiences and sustainability.

This dissertation delves into several key aspects of GEBs, focusing on load shedding, load shifting, and generation. These areas are where significant improvements can be achieved through information technology links. In this dissertation, research will be conducted on the generating and consuming sides to improve these strategies. This dissertation excludes considerations such as battery storage modeling and renewable energy production. Furthermore, the participation of GEBs in demand response and ballancing markets, where electrical flexibility is dealed, is integral to the modern energy ecosystem. By actively participating in these markets, GEBs can capitalize on their ability to dynamically adjust energy consumption and production in response to real-time market signals. Thus, GEBs potentially contribute to several important aspects of grid stability and maximize their economic returns. This dissertation therefore addresses the following points, aiming to improve their effectiveness and further challenge efficient market participation through information technology.

- How to maximize the potential of renewable generation.
- How to manage DERs such as air conditioning systems for modifying load profile.
- How to effectively get rewards through flexibility market participation.

Within the broader scope of GEBs and DERs management, particularly photovoltaic (PV) generation, strategic planning is crucial for evaluating GEB performance and estimating long-term electrical costs. However, the typical method of selling excess solar energy via reverse power flow often leads to instability in the power system. In this context, the role of electric vehicles (EVs) becomes pivotal in effectively utilizing and reducing solar energy waste by filling the spatiotemporal gap in solar energy. This dissertation proposes a novel EV aggregation framework for the spatiotemporal shifting of solar energy, reducing the need for reverse power flow. This framework can contribute to reducing solar energy waste by manipulating pricing strategies for charging and discharging via an EV aggregator. The proposed EV aggregation enables EVs to spatiotemporal shift energy from building to building. Simulation results demonstrate a substantial reduction in solar energy waste, up to 68%, using this novel framework.

Significant research in GEBs focuses on GEB load shedding and shifting strategies through various DERs, particularly HVAC systems. HVAC is crucial due to its high demand within buildings and existing installations, reducing additional costs. This dissertation optimizes HVAC operations by allocating electrical power based on occupancy and outdoor unit capacity, ensuring that the total power consumption complies with peak demand limitations. Various methods, including model predictive control (MPC) and reinforcement learning, are explored for HVAC scheduling. While MPC is effective in long-term planning, its computation time increases with more units, and reinforcement learning requires extensive data and struggles with comfort uncertainty. This dissertation presents a solution that efficiently meets power constraints across multiple units without violating power limitations or sacrificing thermal comfort. The proposed method, balancing electricity costs and thermal comfort through multi-objective optimization, demonstrates that the scheduling of multiple HVAC systems can be achieved efficiently. By integrating the proposed methodology with appropriate HVAC aggregation techniques, a comprehensive framework for energy management in buildings can be provided.

GEBs have evolved from passive power consumers to active participants in the electricity supply and demand balancing market, playing a key role in efficiently integrating renewable energy sources like solar and wind power. This integration is crucial for managing energy variability and preventing grid overloads during peak times. A critical aspect of GEBs' effective market participation involves accurately predicting market transaction prices. This capability is essential for optimizing energy buying or selling strategies, maximizing revenue, and developing efficient energy supply approaches. In this context, the dissertation introduces a novel market price forecasting model tailored for the frequency control ancillary service markets. This model, derived from wholesale market data and considering varying response times, significantly improves the accuracy of the prediction. Experimentally, it has been shown to reduce the root mean square error by 80% compared to existing forecasts from the Australian energy market operator, indicating its effectiveness in supporting the strategic participation of GEBs in energy markets.

様式 7

論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

本論文は、グリッドインタラクティブ・エフィシェント・ビルディング（GEB）に向けた分散型エネルギーリソースマネジメントに関する研究結果をまとめたものであり、以下の主要な成果を得ている。

1.　EVアグリゲータを用いた電力の時空間シフト手法に関する研究

GEBにおいて、太陽光エネルギーの利用における需要と供給の時間的及び空間的ギャップが課題として知られている。時間的ギャップに対してはバッテリが活用される一方、空間的ギャップに対しては電力系統を介した融通が一般的である。しかし、電力系統を介した融通は逆潮流を発生させるため太陽光エネルギーの大量導入時代には電力系統の安定化に大きな影響を与えることが知られている。本論文では、電力系統を介さず電気自動車（EV）を活用する太陽光エネルギーの時間的及び空間的な融通を実現するフレームワークを提案した。評価実験より提案するEVアグリゲータにおいて電力価格を操作することでEVを介して電力の時空間シフトが実現できることを示した。特に、現実的なシナリオで各需要家の無駄電力量の最大68%がEVを介して他の需要家に融通できることが示された。

2.　電力制限下における複数空調スケジューリング手法に関する研究

空調は建物のエネルギー消費の約45%を占めており、GEBにおいて空調のエネルギーマネジメントは重要な役割を担っている。多くの先行研究では居住者の快適性を考慮した空調スケジューリング手法が提案されているが、建物内の複数空調を対象とした快適性を考慮した手法は計算量の観点で実現が困難であった。本論文では、建物全体の電力制限を考慮し居住者の快適性を考慮した複数空調スケジューリング手法を提案した。特に、提案手法は各空調の使用状況に応じて電力資源を割り当てることで部屋数に対してスケーラブルな手法となっている。評価実験より現実的なシナリオで各空調における室内温度と目標温度との平均誤差は0.21℃となり、与えられた電力制限下において4つの部屋を目標温度に保つことに成功した。

3.　需給調整市場における調整力取引価格予測に関する研究

GEBにおける需給調整市場への参画は需要側の調整力創出に向けて注目を浴びている。特に、需給調整市場に参画したGEBが市場からより多くの報酬を得るための市場取引価格予測は多くのGEBの参画を促し更なる調整力の創出に向けて重要な課題である。需給調整市場は様々な区分の市場が混在し互いに影響しあうため、市場取引価格を対象とした予測手法は開発されていなかった。本論文では、対象の取引区分に加え他の区分の価格変化も考慮した市場取引価格予測モデルを提案した。評価実験より、提案した予測モデルはオーストラリアのエネルギー市場運営者（AEMO）が公開している予測データよりも高精度な、予測誤差 7.8 $/MWhでの市場取引価格の予測を実現した。

以上のように、本論文は、GEBにおける包括的なエネルギーマネジメントの実現に向けて有用であり、再生可能エネルギーの更なる普及や低炭素社会の実現に寄与するものと期待できる。よって、博士(情報科学)の学位論文として価値のあるものと認める。