Demand Side Management in Large-Scale Buildings with Intraday Impact

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***Abstract*—The 15 minute intraday electricity market in Europe is approaching, and the market is vital to maintain grid stability in a growing landscape of renewable energy. By facilitating flexible and cross-border trade, it supports the sustainability goals of the EU while improving energy security and efficiency on the continent. The buildings are responsible for approximately 40% of global energy consumption with remarkable amounts of the buildings already using renewable energy sources to make it more complicated. The situation with the 15-minute market can be highly volatile, reflecting immediate demand and supply changes. For instance, sudden weather changes that affect solar or wind generation can drive significant price fluctuations. redistribution of energy sources and suppliers results in high volatility in the energy market—from extremely high to even negative prices. This volatility may significantly impact large consumers with especially complex dynamic operations and multiple stakeholders such as large-scale buildings. Consequently, the paper presents detailed case studies during the day and night on the example of several commercial buildings in Estonia with a one-second measurement interval of HVAC equipment. The technical readiness of buildings to handle flexibility towards the 15-minute market will also be studied.**

***Index Terms*—Smart buildings, energy performance, AI, HVAC, indoor climate, energy flexibility, Demand Side Management, Demand Response**

I. INTRODUCTION

The building sector is a major contributor to global energy consumption, accounting for approximately 40% of total energy use. Furthermore, building operations are responsible for around 27% of annual greenhouse gas (GHG) emissions, making them a critical target for energy efficiency and decarbonization efforts. Recent shifts in energy supply dynamics have led to increased volatility in electricity markets, with price fluctuations ranging from extreme peaks to negative pricing events. This volatility requires advanced energy management strategies that optimize consumption patterns in response to real-time market conditions.

This study proposes a Demand Side Management (DSM) solution that integrates data-driven estimations of a building's thermal inertia with an optimization framework to dynamically shift electrical loads in response to the 15-minute intraday market. The primary objective of this approach is to enhance energy efficiency while maintaining indoor thermal comfort, thereby addressing a complex multi-objective optimization problem. DSM plays a crucial role in enabling real estate owners and managers to implement adaptive energy strategies that respond to price variations, contributing to improved energy efficiency and cost reductions without compromising occupant comfort.

The necessity for such adaptive strategies has become particularly pronounced in the Baltic region following the announcement by regional Transmission System Operators (TSOs) regarding the planned decoupling from Russia-controlled electricity systems in early 2025. This transition culminated in the synchronization of the Baltic electricity networks with the Continental Europe Synchronous Area on February 8-9, 2025. Given this structural shift, large buildings in the region can play a pivotal role in stabilizing the grid by providing rapid load adjustments, an essential capability for integrating variable renewable energy sources.

The findings of this study demonstrate that the technical systems within commercial buildings are capable of responding effectively to the 15-minute intra-market dynamics. By leveraging energy price volatility, buildings can optimize load shifting and electricity consumption, thereby enhancing energy flexibility. The proposed DSM solution is implemented through third-party software that utilizes existing building infrastructure, eliminating the need for additional capital investments while improving overall energy performance. Additionally, as building operations constitute a significant share of GHG emissions, enabling their participation in intraday electricity markets facilitates more efficient trading of renewable energy, aligning with European carbon reduction targets. By functioning as distributed energy storage assets, buildings can maximize renewable integration and mitigate reliance on fossil fuels during peak demand periods. The experimental results further indicate that third-party software solutions can enhance the demand response capabilities of building systems, contributing to their technical readiness as evaluated by the Smart Readiness Indicator under the European Energy Efficiency Directive [1].

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The contribution of the paper is as follows. In the paper, important findings are addressed that underscore the potential of advanced DSM strategies in optimizing building energy performance while supporting grid stability and the broader energy transition. This improvement is achieved by leveraging existing technical equipment and infrastructure, showcasing the potential for technological advancements in the field. This is done by applying an intelligent DSM strategy described in the paper. Results are also presented that indicate the successful implementation of the proposed approach.

The rest of the paper is organized as follows. In Sec. II, related work pertaining to DSM and intraday markets is reviewed. Particular emphasis is placed on the intraday market research due to its overall importance. Next, the technological background is described in Sec. III. Then, in Sec. IV the main results and analysis related to the proposed DSM solution are provided. Finally, in Sec. V conclusions are drawn.

II. RELATED WORK

Demand Side Management (DSM) is a comprehensive framework encompassing various methodologies aimed at optimizing energy consumption across different sectors [2]. A critical aspect of DSM is Demand Response (DR), especially in buildings to enable dynamic energy management and enhance grid stability and operational efficiency. The objective of this study is to demonstrate that DSM and DR strategies can be implemented effectively with intraday capabilities while maintaining a comfortable indoor climate in commercial buildings and allowing risk-free technical operations.

In the context of intraday electricity markets, recent research has focused on designing mechanisms to improve market efficiency and grid reliability. A novel approach has been proposed to establish a fast, last-minute intraday electricity market in Germany, primarily addressing schedule deviations. By incorporating a 15-minute market clearing process, this study highlights how precise adjustments between market closure and power delivery can significantly enhance grid stability [3]. Furthermore, a flexibility-driven market mechanism was introduced to facilitate electricity trading in the final 15 minutes before delivery, with an assessment of effectiveness in integrating renewable energy sources for ten years ahead [4].

Intraday price dynamics have also been extensively investigated, particularly through econometric modeling approaches utilizing high-frequency market data. One such study explores the influence of external factors—including weather variability and fluctuations in renewable energy generation—on short-term electricity price formation [5]. Additionally, an in-depth analysis of trading behaviors in Europe's continuous intraday markets identifies evolving trends driven by the Single Intraday Coupling (SIDC) project, emphasizing the role of market participant strategies in optimizing trading efficiency [6].

Hybrid trading systems, which integrate auction-based and continuous mechanisms, have also been examined for their effectiveness in balancing energy supply and demand. In the case of the French electricity market, research indicates that such systems can enhance market efficiency while addressing energy imbalances [7]. Similarly, studies on the German intraday market have evaluated the impact of 15-minute auction mechanisms in managing variability associated with renewable energy sources, demonstrating their role in mitigating grid instabilities [8]. From a theoretical perspective, equilibrium-based models have been developed to analyze price formation and trading strategies in intraday electricity markets. These models offer insights into optimal trading behavior under conditions of renewable energy variability and market uncertainty [9]. A broader literature review consolidates findings on intraday market dynamics, identifying key drivers such as renewable energy penetration, regulatory policies, and trading behaviors while outlining existing research gaps and potential avenues for future investigation [10].

On the other side, in the commercial sector, optimizing HVAC systems for DSM remains a critical research focus, yet many proposed solutions lack real-world implementations, leading to uncertainties regarding their economic feasibility. The situation remains a challenge in the intraday pricing mechanism due to the inability to impact the demand. One study investigates the potential of using building thermal inertia as a virtual energy storage unit within DSM and DR strategies [11]. Similarly, an experimental study conducted in a large office building assesses HVAC systems in frequency regulation services. While the study demonstrates the feasibility, it also identifies inefficiencies in fast DR applications due to the rapid state transitions required for such services [12].

Advancements in AI-driven energy management have further enhanced HVAC optimization strategies to propose alternative solutions for filling the gap. A space occupancy distribution model leveraging indoor positioning sensors has been developed to dynamically adjust ventilation rates, achieving approximately 20% energy savings [13]. Another approach integrates supervised learning techniques for day-ahead energy price forecasting and thermal environment prediction, thereby improving HVAC efficiency over time [14], another deep learning approach to optimize control strategies for non-stationary multi-zone HVAC systems, yielding a 16% reduction in energy consumption [15]. Data-driven methodologies have also shown promise of potential energy savings of up to 30% in large-scale commercial buildings through adaptive load scheduling and predictive control techniques [16]. Li and Zhang [17] further extend these approaches to enhance decision-making in distributed HVAC systems, effectively reducing overall energy consumption and peak demand.

DR strategies can also contribute to grid stability on a large scale by providing ancillary services to transmission system operators. For instance, an HVAC system in an Italian shopping mall has been analyzed for its capability to deliver ancillary services, highlighting the practical application of DR in commercial environments [18]. Additionally, a real-world DR testbed has been developed to evaluate energy conservation measures and system control architectures, offering insights into the practical deployment of DR strategies [19].

While significant progress has been made in modeling, controlling, and optimizing HVAC systems for DSM, the integration of these strategies into real-world commercial buildings remains a complex challenge. The volatility of energy prices and the potential for large-scale DSM deployment in commercial infrastructure present unresolved questions that require further empirical validation and technological advancements in real buildings.

The paper addressed these challenges in multiple scenarios for realizing the full potential of DSM and DR in buildings while ensuring economic viability and operational feasibility.

III. TECHNICAL BACKGROUND

This section presents a concise overview of the technology employed in the overall solution.

A. *HVAC Operations and Data Acquisition*

In modern large-scale buildings, the Building Management System (BMS) serves as a central component that integrates and interfaces for heating, ventilation, and air conditioning (HVAC) systems, along with their associated sensors and actuators. The BMS incorporates a network interface that enables the retrieval, storage, and control of HVAC-related data to optimize indoor climate conditions or implement cost-saving measures through Demand Side Management (DSM) and Demand Response (DR) strategies. Data exchange between the BMS and external systems is facilitated via an Application Programming Interface (API), the specifics of which depend on the particular BMS software in use. As different BMS platforms require tailored solutions to ensure reliable data communication, remote API access must be customized accordingly. To maintain data security, transmission is safeguarded through encrypted Virtual Private Network (VPN) tunnels.

B. *Digitalization and Data Processing*

Effective building operations require close collaboration between local teams and DSM experts to develop a data-driven DSM solution. The general process for achieving sustainable buildings includes:

1) Digital Twin Creation: Experts establish interconnections between system components to develop a digital twin, enabling AI-driven analytics and cost optimization.
2) Smart Audit Preparation**:** Internal reporting tools facilitate a data-driven audit, identifying energy inefficiencies, indoor climate issues, and mechanical faults, ensuring compliance with international standards.
3) AI-Based Control Implementation: Experts support the technical team in transitioning to AI-based control, configuring the DSM solution based on building characteristics, operational needs, and prior knowledge.

Then, before enabling real-time model-based control, the obtained results are validated by the certified HVAC engineer. The structure with a complete data set for modeling and optimization purposes is depicted in Fig. 1. Leveraging data-driven solutions enables the DR service to operate. Factors including weather, temperature fluctuations, occupancy, energy prices, time of the day, and many more are incorporated into the algorithms to enable proactive data-driven AI decision-making. DR can be enabled/disabled at 60-second intervals for HVAC equipment while the general data acquisition interval is 15 minutes. The DR process for executing activations is compatible with current active reserves including automatic and manual frequency restoration (aFRR/mFRR) according to the European Commission Regulation establishing electricity-balancing guidelines [20].

IV. RESULTS AND ANALYSIS

During the experiment of intraday impact, the data was collected from an air handling unit (AHU) located in a commercial building and integrated with DSM software in real time. The recorded power consumption with 10-second intervals was analyzed during periods of high and low demand and regular load, with a specific focus on the following:

- Initial power levels before DSM intervention with Intraday impact.
- Reaction to DSM control signals.
- Stabilization after power reduction.
- Recovery phase when DSM optimization with intra-day ended, particularly for 15 minutes.

Each dataset was visualized to understand the AHU's load adjustment and performance consistency over time, particularly regarding the operational constraints in commercial buildings where occupancy and environmental requirements vary significantly. Although the measurements are taken at 10-second intervals, the analysis with relevant visualizations is conducted at a 1-minute interval.

A. *Observed Behavior of Air Handling Unit*

The power consumption profile of the AHU under DSM control is shown in two directions with full load, regular load, and minimum load. The recorded power usage demonstrates distinct transitions that align with DSM interventions, characterized by rapid load adjustments.

1) Response to Initial Load Increase: The first scenario in Figure 2a demonstrates the increase in power consumption from average load in response to the use of the advantage of the intraday market in response to DSM software's command. The power increase follows a characteristic pattern where the AHU rapidly increases from its steady-state consumption ($\sim$16 kW) to a maximized operational level ($\sim$25 kW). However, transient fluctuations suggest initial instability before the unit achieves a new operating equilibrium. This adjustment often corresponds with periods of maximum occupancy, where reduced air handling requirements align with DSM goals.

The plot also indicates a brief spike in power consumption before settling into a lower energy state. This could be attributed to the AHU's control system compensating for rapid adjustments, potentially triggering short bursts of additional energy use before stabilizing. After approximately 15 minutes, the system aims to restore the previous consumption profile and reduces the power in minutes. Cyclical power adjustments across DSM events show the AHU's repeated response would

Fig. 1. The general structure of the provided AI-based solution to provide real-time operation of Demand Side Management and Demand Response simultaneously.

have similar reactions throughout the day to have a well-calibrated balance between occupant comfort and energy efficiency. The spikes observed during recovery phases indicate a potential overshoot effect, which may be mitigated by refining control parameters.

2) Demand Minimization and System Stabilization: Figure 2b illustrates a scenario in which the AHU operates at maximal power and suddenly receives a command to operate at minimal power to maximize energy savings. The data shows partial success in maintaining a lower power threshold, with fluctuations caused by the automation system's safety logic. This indicates that while the control algorithm adjusts fan speed, air volume, or pressure significantly, the equipment response at minimal levels may be unpredictable. Therefore, AHU control strategies should aim to balance load reduction with sustained energy savings. The necessity of adaptive control algorithms becomes evident, as they ensure efficient load shedding without compromising indoor conditions. Additionally, the AHU system did not constrain the recovery from minimal to maximum load.

3) Demand Maximization and System Stabilization: The final scenario in Figure 2c illustrates the AHU's response to DSM commands to maximize load and restore the minimum load in 15 minutes. The behavior of AHU reveals a cycle between high and low-power states, suggesting a well-calibrated balance between the two states can be achieved after the first-minute fluctuations and the system would require to ramp up for several minutes gradually. The transient spikes observed during the recovery phase to minimize the load again indicate a potential overshoot effect, which may be mitigated by refining control parameters.

Each event exhibits a rapid increase in power usage following a period of reduced demand, potentially due to AHU compensation for prior energy restrictions. These cyclical variations can be analyzed to optimize DSM schedules, ensuring that power restoration does not lead to excessive peak loads, which could negate the benefits of energy reduction.

4) Intraday Impacts on Commercial Building Performance: The observed trends indicate that DSM interventions lead to a significant impact on adapting to the intraday in HVAC operations. The outcome of those scenarios can have multiple implications:

Energy Savings: The immediate reduction in power demand following DSM control actions with the intraday impact demonstrates the potential for significant energy savings during peak demand periods.

Occupant Comfort: While energy reduction is achieved, further investigation is required to ensure that IAQ and occupant comfort are not compromised due to sudden load reductions, the balance should be managed by the DSM.

Operational Efficiency: Repeated adjustments throughout the day require a balance between energy savings and maintaining consistent environmental conditions. The data suggests that frequent demand shifts may require further calibration to minimize abrupt power fluctuations and ensure optimal air handling performance.

One notable observation is the AHU's recovery time after each DSM event. This recovery period is critical in understanding how quickly the system returns to its baseline operation while maintaining efficiency. If the system exhibits prolonged recovery, it may indicate an overly aggressive DSM strategy with the intraday impact, requiring refinements to maintain comfort levels. In general, the AHU reacts promptly to DSM signals, highlighting its capability for real-time load adjustments without excessive delays or instability.

B. Inertia in Smart Buildings by DSM with Intraday Impact

Demand side management (DSM) is a critical mechanism for managing energy consumption in real estate, enabling dynamic adjustments in electricity prices, even based on real-time fluctuations in the power grid to activate demand response. In commercial buildings, this mechanism is particularly relevant during peak load conditions or in response to unforeseen grid events. A major challenge in intraday implementation lies in the precise estimation and short-term forecasting of indoor temperature variations, which requires

(a) (b) (c)

Fig. 2. The intraday DSM impact in three different scenarios: (a) response to initial load increase; (b) demand minimization and system stabilization; (c) demand maximization and system stabilization. The time series depicting the power consumption profiles were collected on Sep 23, 2024, with the three scenarios starting points at 12:52:30, 14:22:30, and 15:52:30, respectively.

an advanced control framework. Achieving this involves accurately assessing the operational flexibility of HVAC systems and other energy-intensive devices, while simultaneously incorporating constraints to ensure both comfort and efficiency.

The schematic representation of the proposed methodology is provided in Fig. 3, detailing the key stages of the process, including data acquisition, real-time analytics, predictive modeling, and decision-making frameworks.

The approach is utilized in real-world commercial buildings across Europe but excludes kitchen and parking areas. The importance is to ensure a focused assessment of indoor climate dynamics. The impact of HVAC adjustments, particularly the modulation of air handling units, on temperature stability, is analyzed using a comprehensive set of metrics that capture the nuances of indoor climate quality.

To enable effective intraday in real estate, a robust predictive modeling approach is required—one that determines the feasibility of real-time activations at 15-minute intervals while maintaining indoor comfort. The proposed approach integrates ambient temperature as a crucial variable, given its direct influence on HVAC system performance. By leveraging data-driven insights, this approach enhances the adaptability of commercial buildings to intraday DR activations, facilitating more responsive and energy-efficient operations.

V. CONCLUSIONS

Buildings account for approximately 40% of global energy consumption and contribute 27% of annual CO2 emissions. The achievement of climate mitigation and the achievement of EU goals requires significant improvements in building energy efficiency and flexibility. This study highlights the effectiveness of DSM software in modulating AHU energy consumption, contributing to demand flexibility and grid stability, and addressing the potential economic advantage capabilities of the intraday market.

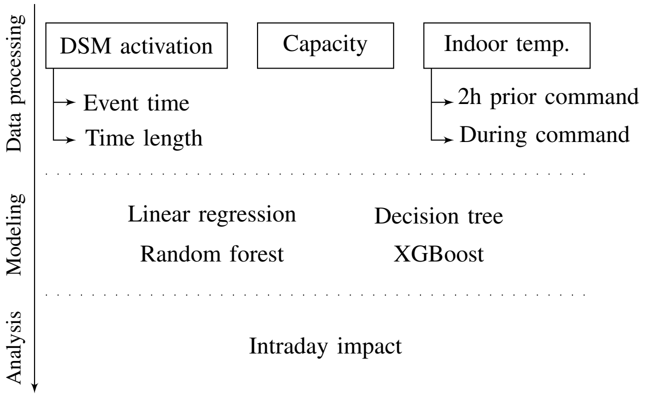

Fig. 3. Schematic pipeline of the proposed approach.

The presented analysis demonstrates that the air handling unit under investigation effectively responds to DSM interventions by rapidly adjusting between operational load levels, though transient fluctuations and power overshoot effects were observed. Initial responses to DSM commands exhibit brief periods of instability and energy spikes before stabilization, suggesting the nessecity for retuning internally running control loops which cannot be directly done via DSM. While the AHU successfully achieves significant load reductions during demand minimization scenarios, fluctuations at minimal loads require the adoption of control algorithms to ensure stable energy savings without compromising indoor comfort. Additionally, cyclical variations between maximum and minimum load states suggest that optimizing DSM scheduling and refining AHU control parameters could further mitigate transient spikes and overshoot, enhancing overall system efficiency and occupant comfort.

Future research should explore DSM strategies in multiple buildings that leverage machine learning to enhance response precision, enabling DSM software to anticipate occupancy variations and environmental demands proactively. Furthermore, refinement of AHU recovery strategies could prevent excessive compensatory energy use, further optimizing efficiency and cost savings.

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