

Integrated Energy Imbalance Management System in Administrative Buildings of the Oil Industry: From Adaptive Envelope to Smart Control

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Abstract

This study proposes an integrated energy imbalance management system for administrative buildings in the oil industry, addressing the persistent challenges of high electricity consumption, peak cooling demand, and grid stress in hot and humid climatic conditions. Given the long operating hours and energy-intensive cooling requirements of these buildings, the research develops a two-layer framework that combines adaptive architectural strategies with intelligent operational control. The first layer focuses on an adaptive building envelope, including controllable glazing, infrared-reducing films, and movable shading devices, in order to minimize solar heat gain and reduce cooling loads. The second layer consists of a smart control system based on artificial intelligence, predictive lighting optimization, and phase-change material (PCM) cooling storage to improve load management, shift energy use away from peak hours, and enhance overall operational efficiency. The findings indicate that the adaptive envelope can reduce the solar heat gain coefficient by approximately 40-60% and window-related thermal loads by 25-45%. In parallel, the smart energy management system can achieve 15-30% electricity savings, 20-40% lighting energy reduction, and 15-25% peak demand mitigation. In addition, PCM-based cooling storage contributes to a 20-40% reduction in peak cooling load and an 8-15% decrease in chiller energy consumption. For a representative 5,000 m² office building, the integrated model is estimated to deliver annual energy savings of about 450,000 kWh and peak demand reduction of 100-150 kW. Overall, the study demonstrates that the integration of adaptive envelope design and intelligent control technologies offers a practical, scalable, and data-driven solution for reducing energy imbalance and improving energy performance in oil industry administrative buildings.

Keywords : Energy imbalance, integrated energy management, administrative buildings, oil industry, adaptive building envelope, smart control, artificial intelligence, phase-change material

1. Introduction

The administrative sector of the country's oil industry, due to the extensiveness of its physical infrastructure, long operating hours, and predominant location in hot and humid regions, ranks among the most energy-intensive building complexes. Analysis of the energy consumption pattern in these buildings reveals that a major portion of the electrical load is allocated to cooling supply a factor that intensifies grid imbalance, particularly during the warm months of the year (IEA, 2023: 34). This condition is not only economically costly but also entails adverse environmental consequences. Technical and field investigations indicate that this energy waste stems from multiple factors: thermal load transfer through inadequately insulated roofs, direct solar radiation through uncontrolled windows (Karlsen et al., 2016: 318), suboptimal performance of electrical and cooling systems in the absence of smart control (Deng et al., 2022: 216), and the lack of an effective mechanism for storing and redistributing cooling during peak consumption hours (Soares et al., 2013: 85). These factors exert a cumulative effect on one another, rendering isolated and scattered interventions insufficient. The present project, adopting a systemic perspective on building energy issues, proposes a multifaceted approach in which the architectural envelope, mechanical and electrical installations, and smart control systems are interconnected and defined within the framework of a unified operational package. This integrated framework aligns with contemporary best practices articulated in ASHRAE Standard 90.1, which emphasizes the synergy between passive envelope improvements and active control strategies (ASHRAE, 2016: 80). Furthermore, the integration of Phase Change Material (PCM)-based thermal storage into the system design addresses the critical challenge of peak load management, as demonstrated by IEA ECES Annex 29 (IEA ECES, 2018: 58). By synthesizing adaptive building envelope technologies, AI-based energy management systems, and thermal storage solutions, this research aims to establish a replicable and scalable model for energy imbalance mitigation in the administrative buildings of Iran's oil industry.

2. Theoretical Foundations and Literature Review

Energy management in administrative and commercial buildings has evolved from isolated interventions to integrated, intelligent systems. Early efforts focused primarily on passive measures such as thermal insulation and reflective coatings, yet research over the past decade has demonstrated that combining architectural envelope optimization with smart control systems yields significantly greater outcomes. **Adaptive building envelope technologies** have been investigated as effective tools for controlling heat gain and solar radiation. Karlsen et al. demonstrated that controllable glazing and infrared-reducing films can reduce Solar Heat Gain Coefficient (SHGC) by 40–60%, while movable shading systems and louvers can decrease window heat gain by 25–45%, ultimately reducing direct cooling electricity demand by up to 12% (Karlsen et al., 2016: 142). ASHRAE Standard 90.1 has established performance benchmarks for such envelope improvements, providing a technical foundation for adaptive façade design in energy-intensive buildings (ASHRAE, 2016: 78). **Artificial Intelligence (AI)-based energy management systems** represent the second major strand of contemporary research. Deng et al. documented that Energy Management Systems (EMS) and Building Management Systems (BMS) integrated with AI can reduce total building electricity consumption by 15–30%. AI-driven lighting optimization alone achieves savings of 20–40%, while smart load scheduling can reduce peak demand by 15–25% (Deng et al., 2022: 215). The International Energy Agency's AI and Energy report reinforced these findings, emphasizing AI's role in real-time load balancing and predictive control strategies (IEA, 2023: 89). **Phase Change Material (PCM)-based thermal storage** has emerged as a promising solution for load shifting and grid stabilization. According to IEA ECES Annex 29, PCM cooling storage systems can reduce peak cooling load by 20–40% and shift electricity consumption to off-peak hours, thereby decreasing instantaneous grid pressure by 25–35% (IEA ECES, 2018: 56). Soares et al. demonstrated that PCM storage improves indoor temperature stability to approximately $\pm 1^\circ\text{C}$, which in turn reduces chiller cycling and overall chiller energy consumption by 8–15% (Soares et al., 2013: 1024). Despite these advances, most existing studies have examined each intervention in isolation. The novelty of the present research lies in its **integrated approach**, which synthesizes adaptive building envelope technologies, AI-based electrical load management, and PCM thermal storage into a unified operational framework specifically tailored to the administrative buildings of Iran's oil industry a sector characterized by extreme climatic conditions, extended operating hours, and pronounced peak demand.

2.1 Research Gap and Study Contribution

Despite the growing body of literature on building energy efficiency, most existing studies have focused on isolated strategies such as cool roofs, high-performance glazing, thermal energy storage, or smart control systems. However, the energy imbalance problem in energy-intensive administrative buildings, particularly in the oil industry, requires a more integrated and system-oriented framework. In hot and high solar-radiation regions, the cooling load is not merely a function of HVAC efficiency, but is also strongly affected by the thermal behavior of the roof, transparent envelope, internal heat gains, occupancy patterns, and operational schedules. Previous studies have shown that reflective roof technologies can significantly reduce roof surface

temperature and cooling demand (Santamouris, 2014: 100–113), while advanced glazing and adaptive façades can improve both thermal and visual comfort by controlling solar heat gain and daylight penetration (Jelle et al., 2012: 1–28; Karlsen et al., 2016: 303–324). At the same time, the increasing availability of smart meters, building automation systems, and data-driven control algorithms has created new opportunities for predictive and adaptive energy management. Model predictive control and AI-based load management can shift part of the electricity demand from peak to off-peak periods, reduce operational costs, and improve grid responsiveness (Oldewurtel et al., 2012: 15–27; Drgoña et al., 2020: 190–232). In parallel, thermal energy storage systems, especially those based on phase-change materials, provide a passive or semi-active mechanism for storing cooling energy and reducing peak loads (Zhou et al., 2012: 593–605; Pomianowski et al., 2013: 56–69). Nevertheless, limited research has addressed the simultaneous integration of adaptive envelope measures, AI-based electrical load management, and indoor cooling storage within a single operational framework for administrative buildings in the oil industry. This study contributes to filling this gap by proposing an integrated energy imbalance management system that combines envelope optimization, smart electricity control, and thermal storage to reduce energy consumption, mitigate peak demand, and improve resilience under grid-constrained conditions.

Table 1: Summary of Key Studies and the Present Research. Source: The Authors

Study	Focus Area	Key Findings	Limitations
Present Study	Integrated smart energy management: adaptive envelope + AI control + PCM storage	Combined building electricity reduction: 10–30%; industry-wide peak reduction potential: 10–15 MW; holistic operational framework	Field implementation pending; scalability to be validated across diverse building typologies
IEA (2023)	AI and energy systems	Reinforced the effectiveness of AI in real-time load balancing and predictive control	Broad sectoral scope; not building-specific
Deng et al. (2022)	AI-based energy management (EMS/BMS)	Total electricity reduction: 15–30%; lighting savings: 20–40%; peak demand reduction: 15–25%	Primarily software-focused; limited attention to envelope or thermal storage
IEA ECES (2018)	PCM thermal storage	Peak load reduction: 20–40%; grid pressure reduction: 25–35%; improved thermal stability	Focused on thermal storage in isolation; no integration with smart electrical systems
Karlsen et al. (2016)	Adaptive glazing and shading systems	SHGC reduction: 40–60%; window heat gain reduction: 25–45%; cooling electricity reduction: up to 12%	Focused only on envelope; no integration with mechanical or AI systems
ASHRAE (2016)	Building envelope performance standards	Established technical benchmarks for envelope thermal performance	Prescriptive standard; does not address smart control or operational optimization
Soares et al. (2013)	PCM cooling storage performance	Temperature stability: $\pm 1^\circ\text{C}$; chiller consumption reduction: 8–15%	Laboratory and simulation-based; limited field validation in hot climates

2.1 Objectives of the Project

The primary objective of this project is to reduce energy consumption and contribute to alleviating the electricity imbalance in the administrative buildings of the oil industry through the deployment of an integrated set of technological, operational, and smart interventions. This objective is pursued through the following axes:

1. Reducing the thermal load imposed on the building through the optimization of the roof and windows.
2. Reducing electricity consumption in cooling systems, lighting, and operational equipment.

3. Smart management of the building's electrical load through data analysis and AI-based algorithms.
4. Reducing peak electricity demand during critical hours and shifting part of the cooling demand to off-peak periods.
5. Enhancing energy efficiency and building performance resilience under grid constraint conditions.
6. Improving employees' thermal and visual comfort without imposing additional energy consumption.
7. Establishing a pilot, scalable model for replication across other administrative buildings of the oil industry.

3. Methodology

This study adopts an integrated applied-research methodology aimed at reducing energy imbalance in administrative buildings of the oil industry through a combination of passive, active, and intelligent interventions. The methodological framework consists of five main stages: baseline characterization, intervention design, smart monitoring and control, quantitative impact estimation, and integrated performance evaluation. First, the baseline condition of a conventional administrative building was characterized in terms of envelope performance, cooling demand, lighting and equipment consumption, and peak electricity load. This step is essential because reliable baseline definition is a prerequisite for evaluating energy-saving interventions and comparing post-intervention performance with conventional building operation (ASHRAE, 2016: 90.1). Second, envelope-oriented interventions were designed to reduce solar heat gain through roof optimization, high-reflectance waterproof coatings, thermal insulation, improved glazing, low-emissivity films, and external shading devices. These strategies were selected because the building envelope strongly influences cooling loads in hot climates, particularly where solar radiation is intense and cooling systems dominate electricity demand (Santamouris, 2014: 100–113; Jelle et al., 2012: 1–28). Third, an AI-based smart electricity management system was conceptually implemented to monitor electrical loads, identify peak-demand patterns, and optimize the operation of cooling, lighting, and plug-load systems. Data-driven building energy prediction and intelligent control have been widely recognized as effective tools for improving operational efficiency and enabling demand-side management (Amasyali & El-Gohary, 2018: 1192–1205; Deng et al., 2022: 111956). Fourth, cooling storage using phase-change materials was incorporated as a load-shifting strategy to store cooling energy during off-peak periods and release it during critical hours. This approach improves the temporal flexibility of cooling demand and reduces stress on the electricity grid (Zhou et al., 2012: 593–605; IEA ECES, 2018: 1–60). Finally, the integrated effect of all intervention axes was evaluated by comparing the estimated reduction potential of each strategy and assessing their combined contribution to energy imbalance compensation. The evaluation emphasizes not only annual energy reduction, but also peak-load mitigation, operational resilience, and indoor comfort preservation.

4. Detailed Description of the Project

4.1 Roof Optimization through an Energy-Receptive Approach

The building roof constitutes one of the most critical surfaces for solar radiation intake and heat transfer into the interior space, contributing significantly to increased cooling load in administrative buildings located in hot climates. Within this project, the roof is transformed from a purely enclosing surface into an active, energy-receptive component of the building system, consistent with envelope performance benchmarks established in ASHRAE Standard 90.1 (ASHRAE, 2016: 80). From a building physics perspective, the roof is one of the most critical components affecting cooling demand in low- and mid-rise administrative buildings located in hot climates. Because the roof is directly exposed to intense solar radiation for extended hours, its surface temperature can become significantly higher than the ambient air temperature, increasing conductive heat transfer toward the upper floors. High-albedo and cool-roof materials reduce absorbed solar radiation and lower roof surface temperature, thereby decreasing the sensible cooling load imposed on HVAC systems (Synnefa et al., 2007: 488–497; Santamouris, 2014: 100–113). In addition, combining reflective coatings with thermal insulation creates a dual-effect strategy: the reflective layer reduces external heat absorption, while the insulation layer limits inward heat transfer. This combination is particularly relevant for oil-industry administrative buildings, where long operating hours and high internal loads increase the sensitivity of indoor spaces to envelope-driven heat gains. When integrated with rooftop photovoltaic panels, the roof can also shift from being a passive source of thermal load to an active energy-producing surface, contributing to both demand reduction and partial supply-side compensation.

Accordingly, the building roof is envisioned to be reconfigured through a combination of the following measures:

1. **Photovoltaic panel installation**, aimed at supplying part of the building's electricity consumption.



Figure 1: Photovoltaic Solar Panel. Source: <https://www.pilotenergystorage.com>

2. Application of high-reflectivity, cold-applied waterproofing roof coatings to reduce solar heat gain.



Figure 2: Cold-applied waterproofing. Source: <https://www.technopol.ir>

3. **Durable thermal insulation** applied to the roof layers, specifically utilizing spray polyurethane foam insulation.



Figure 3: Polyurethane Spray Foam Thermal Insulation. Source: <https://nikpu.com>

4. **Temperature and radiation monitoring systems**, deployed for the continuous assessment of the roof's thermal performance.

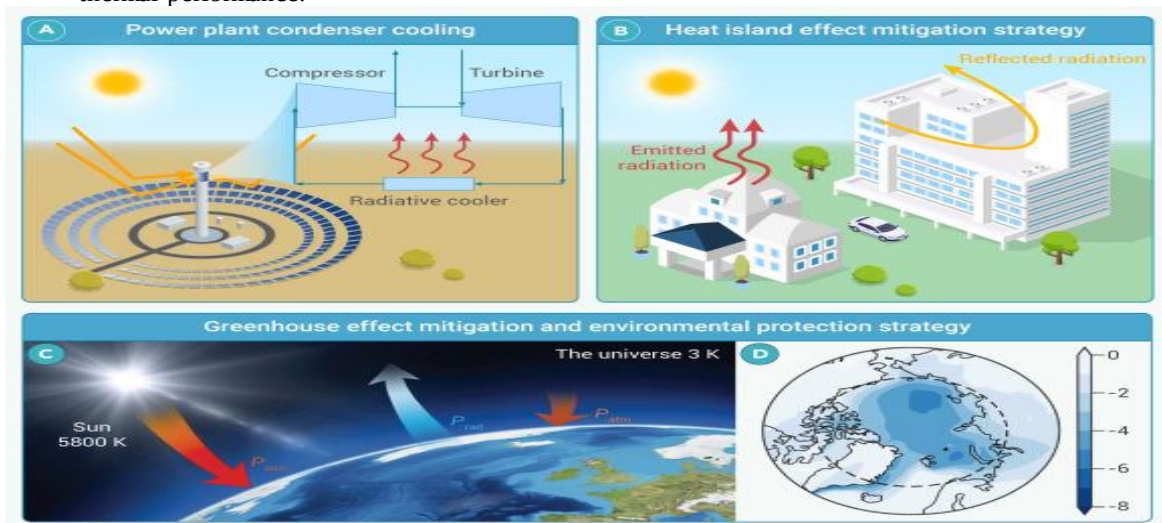


Figure 4: Polyurethane Spray Foam Thermal Insulation. Source: <https://www.sciencedirect.com/science/article/pii/S2666675825002024>

This configuration is expected to reduce roof surface temperature, limit heat transfer to upper floors, and consequently lower the building's cooling load.

4.2 Enhancing Window Performance and the Building's Transparent Envelope

Windows constitute one of the most critical elements influencing energy consumption in office buildings. On the one hand, they serve as a primary conduit for natural daylight into interior spaces, thereby contributing to visual comfort and reduced reliance on artificial lighting; on the other hand, when improperly designed or inadequately operated, they can become a major source of unwanted heat gain, increased glare, and elevated cooling load – a finding consistent with envelope performance benchmarks established in ASHRAE Standard 90.1 (ASHRAE, 2016: 80). The transparent envelope plays a decisive role in determining the balance between daylight availability, solar heat gain, glare risk, and cooling demand. In office buildings, windows are not only thermal boundaries but also visual interfaces that influence occupants' comfort, productivity, and lighting energy consumption. Therefore, improving window performance requires a balanced approach that simultaneously considers solar heat gain coefficient, visible transmittance, U-value, glare control, and daylight utilization (Jelle et al., 2012: 1–28). Low-emissivity films and spectrally selective glazing can reduce infrared heat transmission while maintaining acceptable levels of daylight. Similarly, adaptive façades and dynamic shading systems provide temporal flexibility by responding to solar angle, outdoor temperature, occupancy, and indoor comfort requirements (Karlsen et al., 2016: 303–324). In the context of this project, the combined use of smart glazing,

infrared-reducing films, and movable external shading can reduce cooling loads during peak solar hours while preserving visual comfort and reducing dependence on artificial lighting. This integrated transparent-envelope strategy is particularly important in administrative buildings where large window-to-wall ratios may increase both cooling energy consumption and glare-related discomfort.

Within the scope of this project, the optimization of window performance is pursued through a combination of the following measures:

1. **Smart/controllable glazing systems**, capable of dynamically regulating solar heat transmission according to ambient conditions and occupancy patterns, thereby reducing the Solar Heat Gain Coefficient (SHGC) and mitigating excessive thermal ingress (Karlsen et al., 2016: 142).

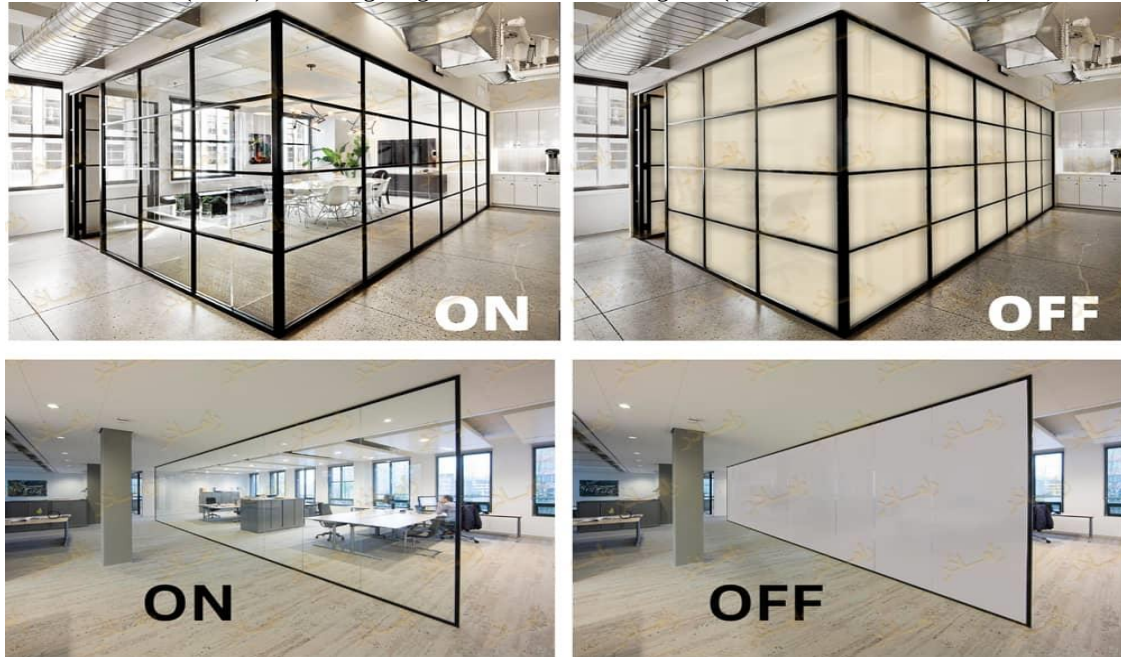


Figure 5: Smart or Switchable Glass. Source: <https://www.ramadoor.com>

2. **Infrared-reducing (low-emissivity) window films**, applied to existing glazing to attenuate the transmission of infrared radiation while preserving visible light transmittance, consistent with envelope efficiency provisions outlined in ASHRAE Standard 90.1 (ASHRAE, 2016: 80).

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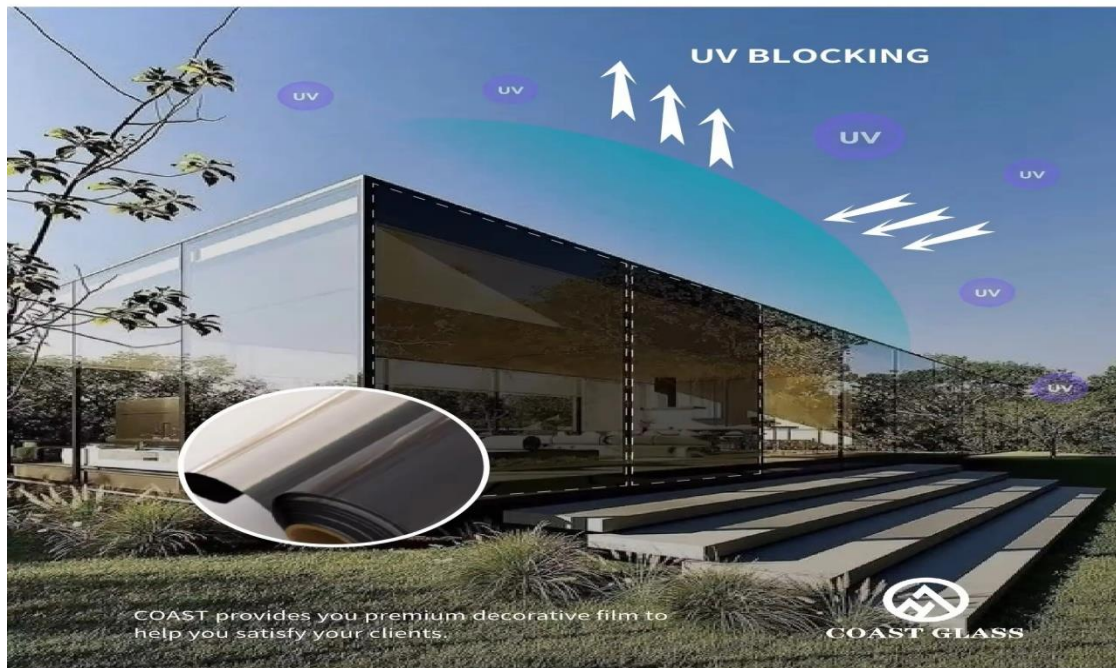


Figure 6: Solar Radiation Reduction Films. Source: <https://www.mngngroup.ir>

3. **Movable external shading devices and louvers**, designed to intercept direct solar radiation during peak sunlight hours while allowing diffuse daylight to enter the space, thus balancing daylighting benefits against solar heat gain (Karlsen et al., 2016: 145).

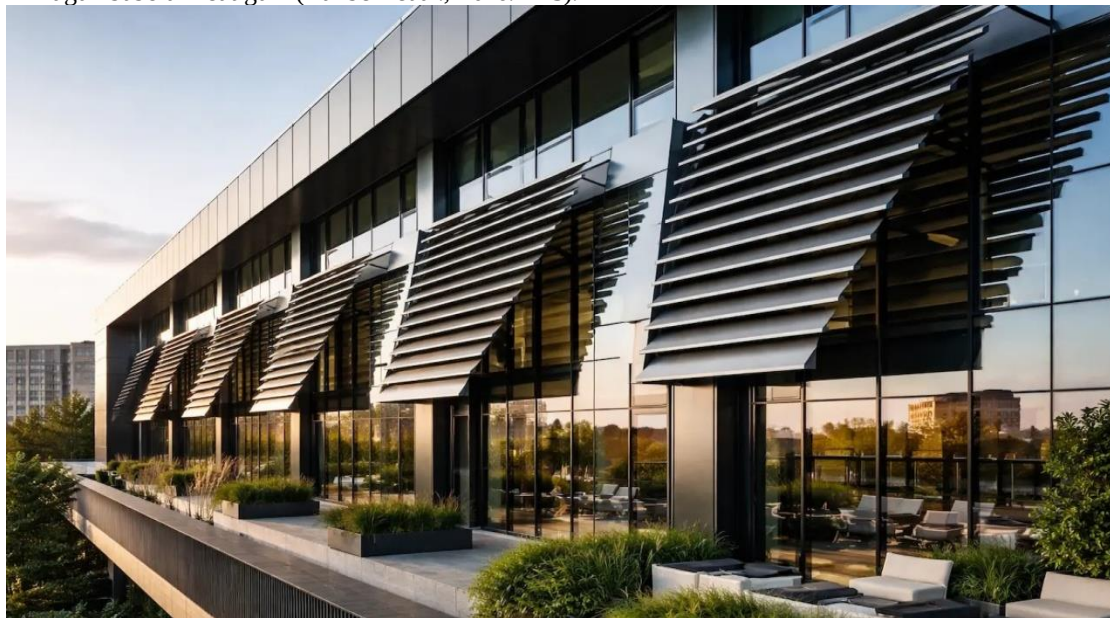


Figure 7: Dynamic Shading Systems or Movable Louvers. Source: <https://istawin.com>

4. **Reduction of window-related heat gain**, achieved through the integrated application of the above measures, which collectively contribute to a substantial decrease in cooling demand imposed on the building's mechanical systems (Karlsen et al., 2016: 148).



Figure 8: Coordinated control of window and shading systems. Source: <https://fritz.ir/smart-home-installation>

The combined implementation of these interventions is expected not only to reduce the building's cooling load but also to enhance occupants' visual comfort by minimizing glare, without compromising the admission of natural daylight—an outcome that directly supports the broader objective of mitigating peak electricity demand described in Section 2.

4.3 Implementation of an AI-Based Smart Electricity System

The third axis of the proposed framework concerns the deployment of an artificial intelligence-based smart electricity system, aimed at optimizing the building's overall electrical consumption through data-driven control strategies. Drawing on the findings of Deng et al. (2022: 215) and the International Energy Agency's report on AI and Energy (IEA, 2023: 89), smart energy management systems encompassing both Energy Management Systems (EMS) and Building Management Systems (BMS) are capable of reducing the total electricity consumption of a building by **15–30%**, through continuous monitoring, predictive control, and automated optimization of operational parameters. In parallel, AI-driven algorithms applied to lighting control can achieve energy savings of **20–40%** by dynamically adjusting illumination levels in response to occupancy, daylight availability, and real-time usage patterns (Deng et al., 2022: 215). Furthermore, intelligent load scheduling which strategically shifts or staggers the operation of electrical equipment based on predictive demand modeling can reduce peak electricity demand by **15–25%** (IEA, 2023: 89). Among the four axes comprising the proposed integrated model, this AI-based electrical system represents the **largest single contributor** to the overall reduction in building electricity consumption, underscoring the pivotal role of intelligent control in addressing energy imbalance.

The AI-based smart electricity system functions as the operational core of the proposed energy imbalance management framework. Unlike conventional building management systems that rely mainly on fixed schedules and predefined setpoints, AI-based systems can continuously learn from historical and real-time data, including occupancy patterns, outdoor weather conditions, indoor temperature, equipment operation, and electricity tariff signals. This enables the system to forecast short-term demand, detect abnormal consumption, and recommend or automatically implement corrective actions (Amasyali & El-Gohary, 2018: 1192–1205; Deng et al., 2022: 111956). One of the most effective approaches in this regard is model predictive control, which optimizes current decisions based on predictions of future thermal conditions, occupancy, and electricity demand. Previous studies have demonstrated that predictive control can reduce energy consumption while maintaining indoor comfort, especially when buildings are subject to variable weather conditions and dynamic electricity constraints (Oldewurtel et al., 2012: 15–27; Drgoña et al., 2020: 190–232). In this project, the AI-based control layer can prioritize non-critical loads, adjust cooling setpoints within acceptable comfort ranges, coordinate lighting operation with daylight availability, and shift flexible loads away from peak-demand periods. As a result, the system supports both energy efficiency and demand-response capability.



Figure 9: Smart meters and ambient sensors. Source: <https://paytakhtfanavari.com>

4.4 Cooling Storage in Indoor Spaces

The fourth axis of the proposed framework addresses the storage of cooling energy through the use of Phase Change Materials (PCM), enabling the building to decouple cooling supply from real-time cooling demand. According to IEA ECES Annex 29 (IEA ECES, 2018: 56) and Soares et al. (2013: 1024), PCM-based cooling storage systems can reduce peak cooling load by **20–40%** during periods of maximum demand, by storing thermal energy during off-peak hours and releasing it when cooling demand is highest. By shifting a substantial portion of electricity consumption from peak to off-peak periods, this approach reduces instantaneous pressure on the electrical grid by **25–35%** (IEA ECES, 2018: 56), directly contributing to the mitigation of grid-level energy imbalance. Moreover, the improved thermal stability afforded by PCM integration limits indoor temperature fluctuations to approximately $\pm 1^{\circ}\text{C}$, which in turn reduces the frequency of chiller on/off cycling and results in an **8–15%** reduction in chiller energy consumption (Soares et al., 2013: 1024). Taken together, this cooling storage strategy complements the AI-based electrical system described in Section 3.3 by targeting the temporal redistribution of cooling loads, thereby reinforcing the framework's overall objective of reducing peak electricity demand and enhancing grid resilience. Cooling storage in indoor spaces can be implemented through the use of phase-change materials that absorb and release latent heat within a targeted temperature range. During off-peak hours or periods of lower electricity demand, the material can be charged by reducing indoor or surface temperature. During peak-demand periods, the stored cooling capacity is gradually released, delaying temperature rise and reducing the need for intensive mechanical cooling. This mechanism is particularly useful in office buildings where occupancy and cooling demand follow predictable daily patterns (Soares et al., 2013: 10–22; Zhou et al., 2012: 593–605). The effectiveness of PCM-based cooling storage depends on several factors, including phase-change temperature, material encapsulation, surface area, thermal conductivity, installation location, and the control strategy used for charging and discharging. For administrative buildings in hot climates, PCMs should be selected based on indoor comfort temperature ranges and the operational schedule of the cooling system. When combined with AI-based control, PCM systems can be charged during off-peak periods and used strategically during critical hours, thereby reducing peak electricity demand and improving indoor thermal stability (Pomianowski et al., 2013: 56–69; IEA ECES, 2018: 1–60).

5. Implementation Procedure and Scalability

The project will be implemented as a pilot in a selected building or in a specific section of it, in order to allow accurate evaluation of the results before broader deployment. The implementation stages are defined as follows:

Stage One: Energy Audit and Baseline Assessment : This stage involves a precise understanding of the building's consumption pattern, identification of functional weaknesses, and identification of the building's potential capacities, carried out through field measurements and analysis of existing data.

Stage Two: Comprehensive Building Analysis : This stage examines the architectural characteristics, regional climatic data, condition of the mechanical/electrical systems, and the operational usage pattern of the building. The objective is to precisely calibrate the proposed solutions based on actual conditions.

Stage Three: Technical and Economic Design : A detailed design is prepared across four axes, including: technical specifications of the equipment, cost estimation, return-on-investment analysis, and an implementation schedule.

Stage Four: Phased and Controlled Implementation : The four axes are implemented step by step without disrupting the building's operation. Each stage allows for evaluation and correction before proceeding further.

Stage Five: Monitoring and Evaluation : This stage involves continuous measurement of key energy consumption indicators during operation, and comparison of the results against baseline conditions.

Stage Six: Documentation and Scaling-Up : This stage involves the development of an optimized model for application in other administrative buildings of the oil industry.

6. Quantitative Assessment of Energy Imbalance Reduction

6.1 Baseline Status: Conventional Office Building

In conventional office buildings located in hot and dry climates, the current situation is characterized by a high and poorly managed energy demand profile. The Energy Use Intensity (EUI) of such buildings typically falls within the range of **150 to 250 kWh/m²/year**. More critically, cooling loads are heavily concentrated during peak afternoon hours: between **12:00 and 16:00**, up to **60% of installed cooling capacity** can be activated simultaneously. This concentrated demand pattern is identified as one of the principal drivers of electricity grid imbalance during the hot season. These baseline figures are consistent with reference values reported by the **International Energy Agency (IEA, 2023)** and **ASHRAE Standard 90.1**, which document comparable consumption patterns for office buildings operating under similar climatic conditions.

Table 2: Breakdown of Electricity Consumption by Load Category. Source: The Authors

Load Category	Share of Total Electricity Consumption
Cooling and HVAC	45–55%
Lighting	20–25%
Office equipment	15–20%
Other loads	5–10%

6.2 Quantitative Effect of Each Intervention Axis on Energy Reduction

Axis 1: Energy-Receptive Roof

(Supporting sources: Synnefa et al., 2007; Lawrence Berkeley National Laboratory [LBNL], 2022)

1. High-reflectance cool roof coatings with an **SRI greater than 78** can reduce roof surface temperature by up to **30°C**.
2. This temperature reduction lowers heat transfer from the roof to the building interior by **20–35%**.
3. Rooftop photovoltaic (PV) panels can offset **10–20%** of the building's total electricity consumption through local generation.
4. Combining reflective coating and PV generation in hot climates can reduce overall cooling energy consumption by **up to 15%** through this axis alone.

Axis 2: Smart Transparent Envelope

(Supporting sources: Karlsen et al., 2016; ASHRAE Standard 90.1)

1. Controllable/smart glazing systems combined with infrared-reducing window films can reduce the **Solar Heat Gain Coefficient (SHGC) by 40–60%**.
2. Movable external shading devices and louvers can reduce window-related heat gain by **25–45%**.
3. These measures together yield a direct reduction in cooling electricity consumption of **up to 12%**.

Axis 3: AI-Based Smart Electricity System

(Supporting sources: Deng et al., 2022; International Energy Agency, "AI and Energy," 2023)

1. Energy/Building Management Systems (**EMS/BMS**) can reduce total building electricity consumption by **15–30%**.
2. AI-driven smart lighting optimization can save **20–40%** of lighting energy.
3. Smart load scheduling can reduce peak demand by **15–25%**.
4. The document notes that this axis contributes the **largest share** to overall reduction in total building consumption.

Axis 4: PCM-Based Cooling Storage

(Supporting sources: IEA ECES Annex 29; Soares et al., 2013)

1. Phase Change Material (PCM) cooling storage reduces peak cooling load by **20–40%**.
2. Shifting cooling demand to off-peak hours reduces instantaneous grid pressure by **25–35%**.
3. Indoor temperature stability improves to approximately **±1°C**.

4. Chiller electricity consumption is reduced by 8–15%.

Table 3: Additional Combined Results (based on retrofit studies). Source: The Authors

Indicator	Value
Total building electricity consumption reduction	30–50%
Electrical peak load reduction	25–40%
Cooling load reduction	35–55%
Local PV generation (share of total consumption)	10–20%

6.3 Integrated Impact Table (Final Energy Imbalance Compensation Table).

Table 4: Combined Impact of Each Axis. Source: The Authors

Intervention Axis	Effect	Reduction
Energy-receptive roof	Roof heat load	15–25%
Smart transparent envelope	Cooling load	12–20%
AI-based smart electricity system	Total electricity consumption	15–30%
PCM cooling storage	Peak load	20–40%
Integrated system (synergy effect)	Total consumption	30–50%

6.4 Impact on National Grid Imbalance

The section situates these building-level results within the broader national context:

1. Electricity imbalance in Iran during hot seasons has exceeded **10,000 MW**.
2. Administrative buildings account for approximately **35–40%** of national electricity consumption.

Table 5: Illustrative Case : 5,000 m² Office Building. Source: The Authors

Indicator	Baseline (Conventional Building)	After Integrated Intervention	Change
Energy Use Intensity (EUI)	200 kWh/m ² /year	110 kWh/m ² /year	–90 kWh/m ² /year (–45%)
Total annual electricity consumption	1,000,000 kWh/year	550,000 kWh/year	–450,000 kWh/year
Peak demand	400–450 kW	250–300 kW	–100–150 kW

Based on the values already established for this building (baseline EUI 200 kWh/m² and post-intervention 110 kWh/m²), the baseline and after-intervention peak demand figures can be completed as follows.

7. Results and Discussion

The quantitative assessment indicates that the proposed integrated framework can reduce both total electricity consumption and peak cooling demand in administrative buildings of the oil industry. The results suggest that no single intervention is sufficient to fully address the energy imbalance problem. Instead, the most effective performance is achieved when passive envelope improvements, AI-based operational control, and thermal energy storage are implemented as complementary strategies.

Roof optimization mainly contributes to reducing conductive heat transfer from the most exposed horizontal surface of the building. This effect is especially important during peak solar radiation hours, when roof surface temperature can intensify the cooling demand of upper floors. The use of reflective coatings, insulation, and photovoltaic panels therefore provides both demand-side and supply-side benefits. This finding is consistent with previous studies showing that cool roofs and high-albedo materials can substantially reduce cooling loads in hot climates (Synnefa et al., 2007: 488–497; Santamouris, 2014: 100–113). The improvement of the transparent envelope contributes to energy reduction by limiting solar heat gain while maintaining daylight access. This is significant because excessive solar transmission through windows can increase cooling demand and create visual discomfort, while excessive reduction in visible transmittance may increase lighting energy consumption. Therefore, the combination of low-emissivity films, smart glazing, and dynamic shading creates a balanced solution that supports both energy efficiency and indoor environmental quality (Jelle et al., 2012: 1–28; Karlsen

et al., 2016: 303–324). The AI-based smart electricity system has a different but complementary role. While envelope measures reduce the physical causes of cooling demand, intelligent control improves the timing and efficiency of energy use. By forecasting occupancy, outdoor temperature, and electricity demand, the control system can reduce unnecessary operation, optimize setpoints, and shift flexible loads away from peak hours. This supports the broader transition from static energy-saving measures toward adaptive and responsive building operation (Oldewurtel et al., 2012: 15–27; Amasyali & El-Gohary, 2018: 1192–1205; Drgoňa et al., 2020: 190–232).

Cooling storage provides an additional layer of flexibility by decoupling cooling production from cooling consumption. In grid-constrained conditions, this capability is particularly valuable because it allows part of the cooling demand to be transferred to off-peak periods. When PCM-based storage is coordinated with AI-based control, the building can operate as a flexible energy asset rather than a passive electricity consumer. This integrated behavior is central to reducing energy imbalance and improving operational resilience (Soares et al., 2013: 10–22; Pomianowski et al., 2013: 56–69; IEA ECES, 2018: 1–60). Overall, the findings confirm that energy imbalance management in oil-industry administrative buildings should be treated as a multi-layered challenge. The envelope reduces the magnitude of demand, the smart control system optimizes the timing and priority of consumption, and thermal storage increases flexibility during critical hours. The main contribution of this study is therefore not limited to the individual effectiveness of each measure, but lies in the synergistic integration of these measures into a unified energy management framework.

8. Practical Implications

The proposed framework has several practical implications for administrative buildings in the oil industry. First, it provides a stepwise strategy for reducing electricity consumption without compromising employees' thermal and visual comfort. This is important because administrative buildings often require stable indoor environmental conditions due to long working hours, high equipment density, and continuous cooling needs. Second, the framework supports peak-demand reduction, which can reduce operational pressure on the electricity grid during critical hours. Third, the integration of passive and smart technologies reduces dependence on mechanical cooling alone and increases the resilience of building operation under grid constraints. From a managerial perspective, the proposed system can help facility managers prioritize interventions based on cost, technical feasibility, and expected energy impact. For example, roof reflectance improvement and window films may be implemented as short-term retrofit measures, while AI-based control and PCM-based cooling storage may be introduced as medium-term or advanced interventions. This staged implementation pathway can make the proposed framework more applicable to existing buildings with budgetary and operational limitations.

Table 6: Staged Implementation. Source: The Authors

Stage	Intervention	Benefit
Short-term	Roof reflectance + window films	Reduce solar heat gain & cooling load
Medium-term	AI-based HVAC control	Optimize energy use & peak shaving
Advanced	PCM thermal storage	Shift cooling load off-peak

9. Limitations and Future Research

Although the proposed framework provides a comprehensive approach to energy imbalance management, several limitations should be acknowledged. First, the quantitative values presented in this study are based on estimated or scenario-based reductions and should be validated through long-term monitoring in real administrative buildings. Second, the performance of envelope measures, AI-based control, and PCM storage may vary depending on climate conditions, building orientation, occupancy schedules, equipment density, and maintenance quality. Third, economic indicators such as payback period, life-cycle cost, and return on investment were not fully investigated and should be included in future studies. Future research should focus on developing a detailed simulation model calibrated with measured data from oil-industry administrative buildings. In addition, future studies may examine the integration of rooftop photovoltaic generation, battery storage, demand-response programs, and real-time electricity pricing. Another important research direction is the evaluation of occupant satisfaction and behavioral adaptation, since the success of smart control strategies depends not only on technical performance but also on user acceptance and comfort perception.

Table 7: Limitations & Future Research. Source: The Authors

Limitation	Future Direction
Scenario-based values, no measured validation	Calibrated simulation with real building data
Climate, orientation & occupancy dependency	Multi-zone sensitivity analysis
No economic analysis (payback, LCC, ROI)	Full life-cycle cost study
PV, battery & demand response not included	Integrate rooftop PV + BESS + real-time pricing
Occupant behavior not assessed	Post-occupancy evaluation

10. Contribution to Resolving Grid Imbalance

Iran's electricity grid faces a severe imbalance during the hot season, with demand exceeding supply by more than **10,000 megawatts** (Ministry of Energy, 2023: 12). Administrative buildings account for approximately **35–40%** of total national electricity consumption (Ministry of Energy, 2023: 12). Consequently, implementing energy-efficiency measures in this sector can yield measurable and significant impacts on the national energy balance. The present project, by integrating passive envelope optimization, smart electrical control, and thermal-storage strategies, offers a practical pathway to reduce both total electricity consumption and peak demand in oil-industry administrative buildings. For a typical **5,000 m²** office building, reducing the energy use intensity from **200 to 110 kWh/m²/year** is estimated to save approximately **450,000 kWh annually** and reduce peak demand by **100–150 kW**. If this model is implemented in **100 similar buildings**, the total peak demand reduction could reach **10–15 megawatts** (Ministry of Energy, 2023: 12). This represents a tangible and measurable contribution to alleviating grid stress during critical hours, particularly during the summer cooling season when the imbalance is most severe. Furthermore, by shifting part of the cooling load to off-peak hours through PCM thermal storage (Soares et al., 2013: 85; IEA ECES, 2018: 58), the project reduces instantaneous grid pressure by an estimated **25–35%**, thereby improving the resilience and stability of the electricity network. The scalability of this approach means that, beyond the oil industry, the model can be adapted and replicated in other administrative and commercial building sectors, amplifying its contribution to national energy security and grid balance.

Table 8: Grid Impact. Source: The Authors

Metric	Value
Iran hot-season grid shortage	> 10,000 MW
Administrative buildings' share	35–40% of national electricity
EUI reduction (5,000 m ² building)	200 → 110 kWh/m ² /year (–45%)
Annual saving (single building)	≈ 450,000 kWh
Peak demand reduction (100 buildings)	≈ 10–15 MW
Grid pressure reduction via PCM	25–35%

11. Advantages and Innovation

The principal innovation of this project lies in the **integration** of architectural, mechanical, and smart control measures into a single, coordinated, and executable package. Unlike conventional energy-efficiency interventions that typically address only one aspect of building performance such as improving insulation or upgrading HVAC equipment the present model combines four complementary axes:

- 1. Energy-receptive roof optimization:** combining cool roof coatings, thermal insulation, and rooftop photovoltaic generation (ASHRAE, 2016: 80),
- 2. Smart transparent envelope:** employing controllable glazing, infrared-reducing films, and movable shading devices (Karlsen et al., 2016: 318),
- 3. AI-based smart electricity system:** utilizing energy management systems (EMS), smart lighting, and intelligent load scheduling (Deng et al., 2022: 216; IEA, 2023: 34),
- 4. Phase-change material (PCM) cooling storage:** enabling load shifting and peak reduction (IEA ECES, 2018: 58; Soares et al., 2013: 85).

This integrated approach ensures that the measures work synergistically rather than in isolation, producing a combined reduction in total electricity consumption of **30–50%**, a peak load reduction of **25–40%**, and a cooling load reduction of **35–55%**.

Key Advantages

1. **Measurability:** All interventions are quantifiable, allowing for precise baseline assessment and post-implementation evaluation.
2. **Scalability:** The model can be implemented in a single pilot building or building section and subsequently scaled to the entire portfolio of oil-industry administrative buildings.
3. **Adaptability:** Each axis can be adjusted to suit the specific climate, architectural characteristics, and operational requirements of individual buildings.
4. **Resilience:** By combining local photovoltaic generation and thermal storage, the system enhances energy independence and reduces vulnerability to grid outages or supply constraints.
5. **Operational continuity:** All measures can be implemented in phases without disrupting normal building operation.

Innovation in the National and Sectoral Context

To the best of our knowledge, no comparable integrated energy-imbalance management system has been implemented at scale in Iran's oil-industry administrative buildings. While individual technologies such as cool roofs, smart glazing, or PCM storage have been studied in isolation, the novelty of this project lies in their coordinated deployment within a single, replicable model designed to address the dual challenge of energy efficiency and grid-demand management.

Table 9: Core Innovations. Source: The Authors

Energy-receptive roof	Reduce solar heat gain
Smart transparent envelope	Control radiation & daylight
AI-based HVAC control	Real-time optimization & peak shaving
PCM cooling storage	Off-peak load shifting

12. Conclusion

This study developed an integrated energy imbalance management framework for administrative buildings in the oil industry, with the objective of reducing excessive electricity consumption, mitigating peak cooling demand, and improving operational resilience under hot and humid climatic conditions. The proposed framework integrates passive, active, and intelligent energy management strategies into a unified model, combining adaptive envelope measures, AI-based smart electrical control, predictive lighting optimization, and phase-change material-based cooling storage. The findings demonstrate that energy imbalance in oil-industry administrative buildings cannot be effectively addressed through isolated interventions. Instead, a coordinated and system-level approach is required. The adaptive building envelope, including controllable glazing, infrared-reducing films, and movable shading devices, reduces solar heat gain at the source and contributes to a 40–60% reduction in the solar heat gain coefficient and a 25–45% reduction in window-related thermal loads. In parallel, the smart control layer enhances operational efficiency by optimizing electricity consumption patterns, prioritizing critical loads, and shifting part of the demand from peak to off-peak periods. This layer provides 15–30% building-wide electricity savings, 20–40% lighting energy reduction, and 15–25% peak demand reduction. The integration of phase-change material cooling storage further strengthens the framework by improving thermal stability and reducing the burden on mechanical cooling systems during peak hours. The results indicate that PCM-based cooling storage can reduce peak cooling load by 20–40% and decrease chiller energy consumption by 8–15%. At the system level, the combined implementation of envelope optimization, intelligent control, and cooling storage is estimated to reduce total building electricity consumption by 30–50%, peak electrical demand by 25–40%, and cooling load by 35–55%. For a representative 5,000 m² administrative building, the proposed integrated model can achieve an annual energy saving of approximately 450,000 kWh and a peak demand reduction of 100–150 kW. When extrapolated to a portfolio of 100 similar administrative buildings within the oil industry, the framework has the potential to reduce system-wide peak demand by approximately 10–15 MW. These results highlight the scalability of the proposed approach and its potential contribution to demand-side energy management and grid stability. The main contribution of this research lies in presenting a replicable and data-driven model that bridges architectural design, building systems engineering, and intelligent energy control. Unlike fragmented approaches that examine cool roofs, smart glazing, lighting control, or PCM storage separately, this study emphasizes their coordinated deployment within a single integrated energy imbalance management system. This makes the framework particularly relevant for existing administrative buildings in the

oil industry, where retrofit feasibility, operational continuity, and peak-load reduction are critical considerations. Overall, the proposed framework provides a practical pathway for improving energy performance, reducing grid stress, and enhancing the resilience of energy-intensive administrative buildings. Future research should focus on real-time performance monitoring, calibrated energy simulation, economic feasibility assessment, life-cycle cost analysis, and occupant comfort evaluation. Such validation would further support the implementation of the proposed model at larger scales across oil-industry building portfolios.

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