# A Graph-based Multi-Agent Framework for Distributed Zero-Energy Flow Management in Smart Buildings

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**Resumen** This paper presents a distributed energy management framework for smart buildings based on a graph-based multi-agent system. The proposed approach models the building energy system as an extended graph where nodes represent autonomous agents (loads, renewable generators and storage systems) and edges represent multiple interaction channels enabling both energy and information exchange. Each agent operates based on local information and interactions with neighboring agents, allowing the system to evolve without centralized control. The objective of the framework is to achieve a net-zero energy flow condition through decentralized coordination. The paper describes the proposed modeling approach, agent behaviors and interaction mechanisms. Moreover a discussion on the potential advantages and challenges is presented. At this stage, the framework focuses on the structural and predictive components, while the distributed decision-making layer remains to be implemented and validated. This work establishes a foundation for future simulation-based validation and further development of distributed energy management strategies.

**Keywords:** Multi-Agent Systems, Graph-based Modeling, Distributed energy management, Renewable energy forecasting

# Gestión de energía con balance neto cero en edificios inteligentes a partir de un enfoque multiagente basado en grafos

**Resumen** Este trabajo presenta un enfoque de gestión distribuida de energía para edificios inteligentes basado en un sistema multiagente representado mediante grafos. El enfoque propuesto modela el sistema energético del edificio como un grafo extendido, donde los nodos representan agentes autónomos (cargas, generadores renovables y sistemas de almacenamiento) y las aristas representan múltiples canales de interacción que permiten tanto el intercambio de energía como de información. Cada agente opera a partir de información local e interacciones con agentes vecinos, lo que permite que el sistema evolucione sin control centralizado. El objetivo de la metodología es alcanzar una condición de flujo energético neto cero mediante coordinación descentralizada. El artículo describe el enfoque de modelado propuesto, el comportamiento de los agentes y los mecanismos de interacción. Asimismo, se presenta una discusión sobre las posibles ventajas y desafíos del enfoque. En esta instancia, la propuesta se enfoca en los componentes estructurales y predictivos, mientras que lo relacionado con el control distribuido constituye una línea de trabajo futura cuya implementación y validación aún están pendientes. Este trabajo establece una base para futuras validaciones mediante simulación y para el desarrollo de estrategias de gestión energética distribuida.

**Palabras clave:** Sistemas Multiagente, Modelo basado en Grafos, Gestión Distribuida de Energía, Predicción de energía renovable

## 1. Introduction

Renewable energy sources integration in buildings, particularly photovoltaic systems, has introduced new challenges in energy management due to the intermittency of the resource and the inherent uncertainty of the demand. As buildings evolve toward more complex and interconnected energy systems (including distributed generation, storage, and flexible loads), there is a growing need for scalable and adaptive management strategies (Gonzales-Zurita et al., 2026).

Traditional energy management systems (EMS) are commonly based on centralized optimization approaches, particularly Model Predictive Control (MPC), which leverages forecast information to optimize system performance under operational constraints. MPC has demonstrated strong capabilities in handling multiobjective optimization problems and incorporating predictive information into decision-making processes (Michailidis et al., 2025). However, recent review studies highlight that, as building energy systems become more complex and interconnected, these approaches face increasing challenges related to scalability, computational burden, and model dependence. In particular, the growing integration of heterogeneous components, data-driven methods, and advanced control strategies has significantly increased the complexity of EMS design, revealing limitations in centralized formulations and motivating the exploration of more flexible solutions (Michailidis et al., 2024).

To address these limitations, distributed control strategies based on multi-agent systems have been proposed (Olivares et al., 2014). In these approaches, system components are modeled as autonomous agents that interact locally to achieve coordinated behavior. Such frameworks offer improved scalability and adaptability, and have been successfully applied in microgrids and smart grid scenarios. However, many existing multi-agent approaches focus primarily on coordination mechanisms and do not fully exploit predictive information or flexible system representations (Kazim et al., 2025).

Agent-based modeling (ABM) has also been widely used as a tool to represent and simulate complex energy systems. By capturing local interactions among heterogeneous agents, ABM enables the study of emergent behaviors in decentralized environments (Pudane, 2017). Nevertheless, most ABM-based studies are oriented toward simulation and analysis rather than the design of distributed control strategies, and often lack integration with forecasting mechanisms.

In parallel, graph-based representations have been extensively used to model energy networks, particularly in the context of electrical grids. These models provide a natural way to describe connectivity and energy flows. However, traditional graph representations typically assume static node behavior and single-type interactions, which limits their applicability in dynamic systems with heterogeneous components and multiple interaction layers (Cervellini et al., 2023).

Despite these advances, the combined use of distributed multi-agent control, flexible graph-based representations, and predictive information for achieving net-zero energy flow in building energy systems remains insufficiently explored.

In this context, this paper proposes a distributed graph-based multi-agent framework for energy management in smart buildings. The system is modeled as an extended graph in which nodes represent autonomous agents with embedded behavior, and edges represent multiple interaction channels enabling both energy and information exchange. The proposed framework incorporates predictive information of solar generation and load demand to support anticipatory decision-making at the agent level. The overall objective is to achieve a net-zero energy flow condition through decentralized coordination, without relying on centralized control.

## 2. Proposed Framework

### 2.1. Graph-based representation

The building energy system is modeled as a graph $G = (Vertex, Edge)$, where each vertex represents an autonomous agent, and each edge represents a connection between agents as presented in Fig. 1. Unlike traditional graph representations, which model a single type of interaction, the proposed framework allows the modeling of different types of interaction, such as energy transfer and information exchange between agents. Furthermore, each agent is associated with a structured representation containing parameters and state variables that describe the behavior of the agent. This allows modeling heterogeneous components such loads, renewable sources and storage systems, including their dynamic characteristics(Cervellini et al., 2023).

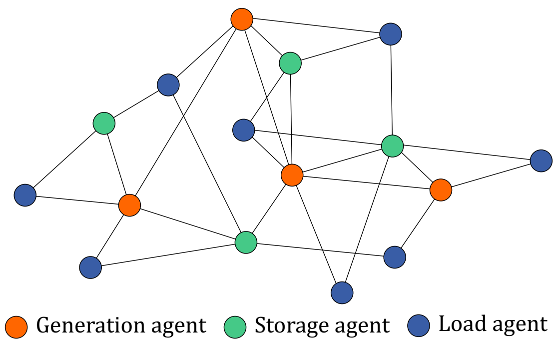


**Figura 1.** Graph-based representation

Each edge is defined, also, as a multi parameter structure enabling the simultaneous representation of different interaction types, such as energy exchange, information flow and communication constraints, among others.

The framework considers three main types of agents: Load agents (characterized by time-varying energy demand), generation agents (representing renewable energy sources with variable output) and storage agents (characterized by energy capacity, state of charge, and bidirectional energy flow).

Agents interact through the graph structure by exchanging both energy and information. Energy exchange occurs locally between connected agents, based on availability and demand, while information exchange includes state variables and predicted values.

The system evolves in discrete time steps, where each agent follows a perception–decision–action cycle as presented in Fig. 2. At each time step, agents first perceive their local state and gather information from neighboring nodes. This information is then used to update internal variables and generate local forecasts. Based on these updated states and previous estimations each agent performs a decision-making process that determines its action. Finally, agents execute energy exchanges with their neighbors, resulting in the overall system evolution through decentralized interactions.

This decentralized mechanism enables the emergence of coordinated behavior without centralized supervision.

### 2.2. Integration of predictive Information

The proposed framework incorporates predictive information in the form of forecasted solar generation and load demand. These predictions are used by agents to anticipate future system states and adjust their behavior accordingly.

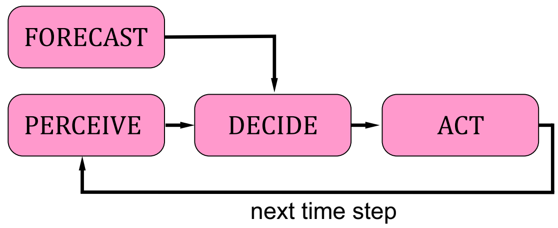


**Figura 2.** Perception-decision-action cycle

For example, storage agents may schedule charging or discharging actions based on expected future imbalances, while load agents may adapt their consumption patterns when flexibility is available. The integration of predictions enhances the systems ability to approach the desired energy balance proactively.

### 2.3. Zero-energy Flow Objective

The primary objective of the system is to achieve a net-zero energy flow condition within the building. This condition can be expressed as:

$$\sum_{t}(E_{generation}(t) + E_{storage}(t) - E_{consumption}(t)) = 0 \tag{1}$$

over a given time horizon.

Rather than enforcing this condition through centralized optimization, the proposed framework seeks to achieve it through local interactions and distributed decision-making among agents.

## 3. Discussion and future work

The proposed distributed framework offers several advantages. It enables scalability by avoiding centralized computation, supports flexibility through heterogeneous agent behavior, and enhances robustness by relying on local interactions. Additionally, the integration of predictive information allows agents to anticipate future conditions, improving system performance.

However, the absence of centralized coordination introduces challenges. The system may exhibit oscillatory behavior or fail to converge under certain conditions. The design of local decision rules and interaction mechanisms is therefore critical to ensure stability and efficiency.

Furthermore, the effectiveness of the framework depends on the accuracy of predictions and the structure of the interaction network. These aspects will be key factors in future implementations.

At the current stage of development, significant progress has been achieved in the implementation of the underlying modeling components. In particular, a functional implementation in Ç"language of the extended graph representation has been developed, allowing the definition of agents with embedded behaviors and multiple interaction channels. Additionally, predictive models for both renewable energy solar resources—and load demand have been implemented and integrated into the framework. These elements provide the necessary informational layer to support anticipatory decision-making.

However, the distributed decision-making mechanism that governs agent interactions and enables coordinated system behavior has not yet been fully implemented. This component represents the core challenge of the proposed framework, as it requires the design of local decision rules that ensure global objectives, such as achieving a net-zero energy flow, emerge from decentralized interactions without centralized supervision.

The absence of this decision layer implies that, at present, the framework is limited to structural representation and predictive capability, without closed-loop operational behavior. Nevertheless, the current implementation provides a foundation for the development and validation of distributed control strategies.

Future work will focus on the formulation and implementation of agent-level decision policies, potentially based on local optimization, consensus algorithms, or rule-based coordination mechanisms. The evaluation of the proposed framework will be carried out through simulation studies, analyzing system performance under different scenarios of generation variability and load uncertainty.

## 4. Conclusion

This paper presented a distributed graph-based multi-agent framework for energy management in smart buildings, aimed at achieving a net-zero energy flow condition. By combining agent-based modeling, flexible graph representations, and predictive information, the proposed approach provides a novel foundation for decentralized energy management. It should be noted that, at the current stage, the contribution is conceptual: the decision-making layer that closes the control loop has not yet been implemented, and the framework should be understood as a structural and methodological basis rather than a validated control solution.

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