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Holistic Conceptualization of a Novel AI-Based Building Energy Management System for Positive Energy District Development

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INTRODUCTION & AIM

The development of positive energy districts (PEDs) is crucial for the transition towards climate-neutral European cities and to meet UN Sustainable Development Goals and European Green Deal objectives. PEDs integrate renewable energy technologies, energy-efficient designs, and intelligent control strategies to achieve an annual energy balance and surplus generation.

The growth of urban energy systems, renewable generation fluctuation, demand variability, and the need of multi-scale energy storage requires advanced energy management strategies to enhance efficiency, resilience, and cost-effectiveness. Artificial intelligence (AI) and Machine Learning (ML) techniques are demonstrated to be crucial to ensure the compatibility of energy systems, enabling automations and the design of novel smart indicators for energy consumption.

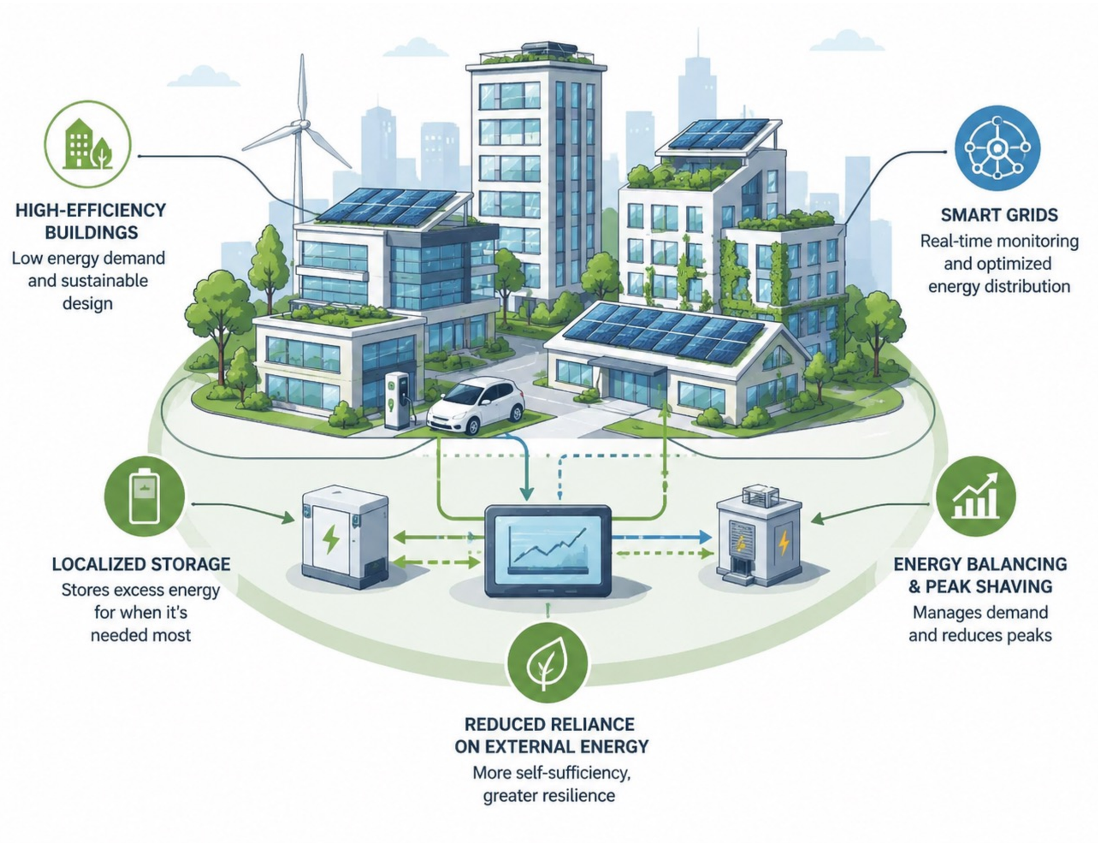

Fig.1 Architecture of a Climate-Neutral Positive Energy District

METHOD

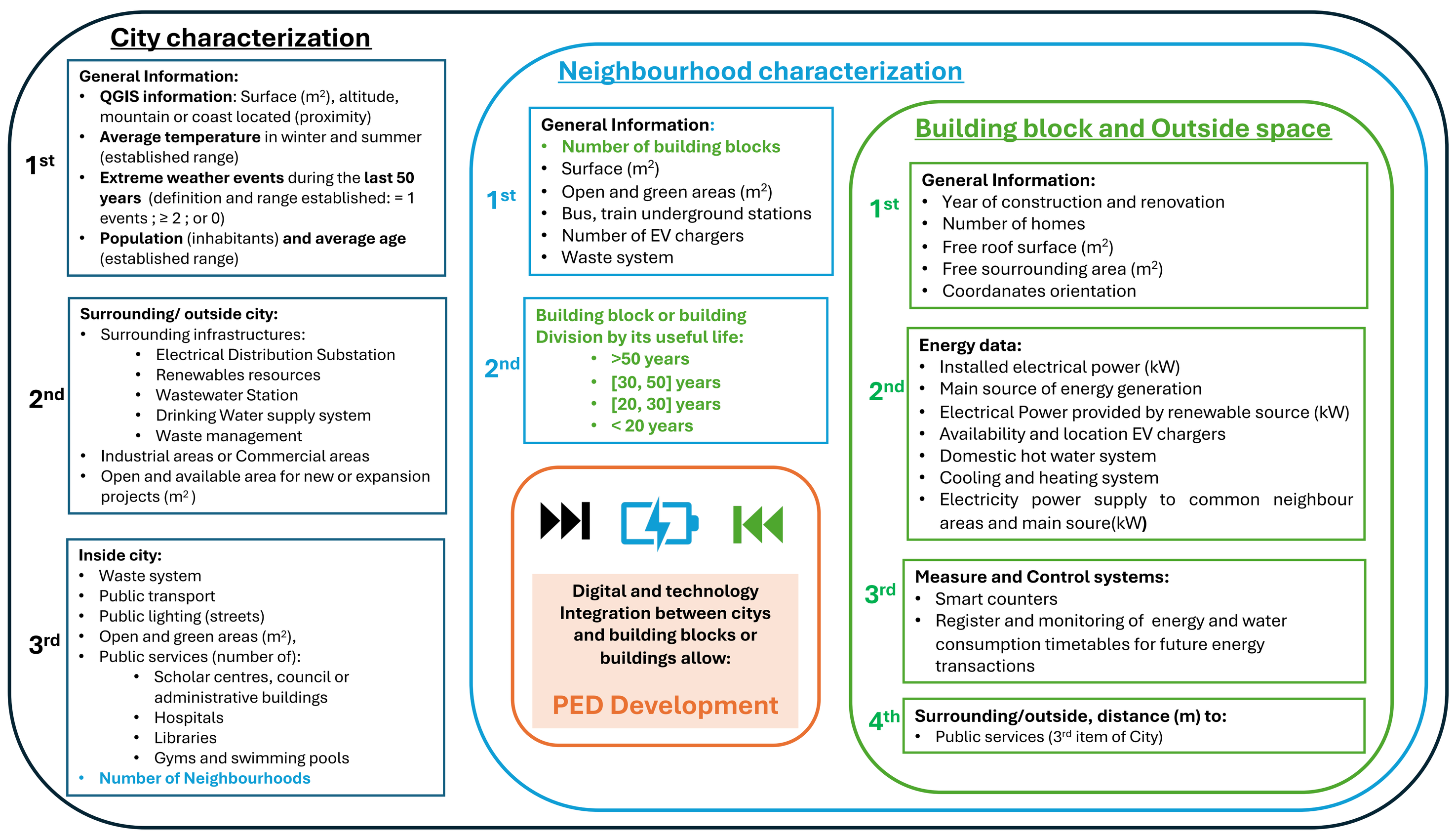

Fig.2 Conceptual methodology for PED charcteristics identification

RESULTS & DISCUSSION

Results reveal the existence of research gaps among PEDs deployment strategies. Above all, current studies mainly focus on building energy demand while overlooking outdoor spaces (i.e. parks, squares) and urban systems such as water, waste management, public lighting, transportation. Existing methodologies often target small-scale or newly developed districts, neglecting challenges in established urban areas with no latest technologies or updated infrastructure installed. The holistic methodology, here implemented, takes into account the concept of 'the space in between' to better define district boundaries and promote fair energy transitions. Furthermore, energy sharing between residential, commercial, and industrial users, including energy-intensive processes has been considered in order to address energy poverty, inefficient buildings, and infrastructure adaptation. Concurrently, enhancing the resilience and efficiency of energy infrastructure has become an urgent strategic priority. On a global scale, extreme weather events continued to occur at alarming levels being responsible for approximately 80% of power outages [1] [2]. Amomg theem, extreme winds were identified as the main factor disrupting overhead power lines, accounting for approximately 28–40% of the examined windstorm-related events [3]. A PRISMA-based systematic review has been carried out and it shows that Positive Energy Districts (PEDs) can significantly enhance energy resilience and climate adaptation. PEDs integrate high-efficiency buildings, renewable energy generation, and localized storage to achieve energy balancing, peak shaving, and reduced dependence on external energy sources [4] [5] [6] [7].

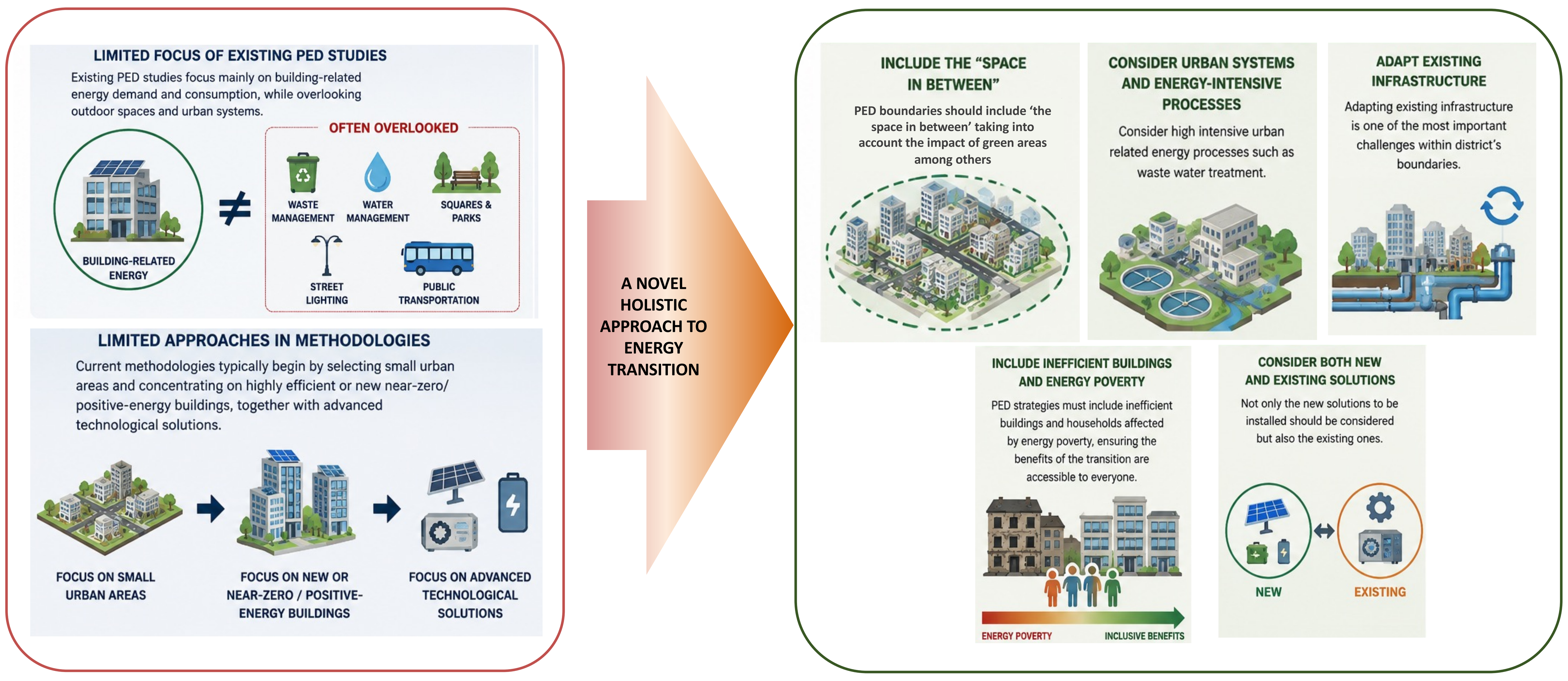

Fig.3 Analysis of the existing ambiguities in PED deployment and definition of to a novel holistic approach to energy transition

Digitalization, AI-driven control systems, and real-time grid monitoring improve the management of distributed energy resources, predict equipment failures, and can reduce outage durations by 30–50% [8] [9]. Additional solutions include Grid-Enhancing Technologies, such as Dynamic Line Rating, Virtual Power Plants that aggregate distributed resources, and smart microgrids that ensure continuity of critical services and community energy security [10] [11].

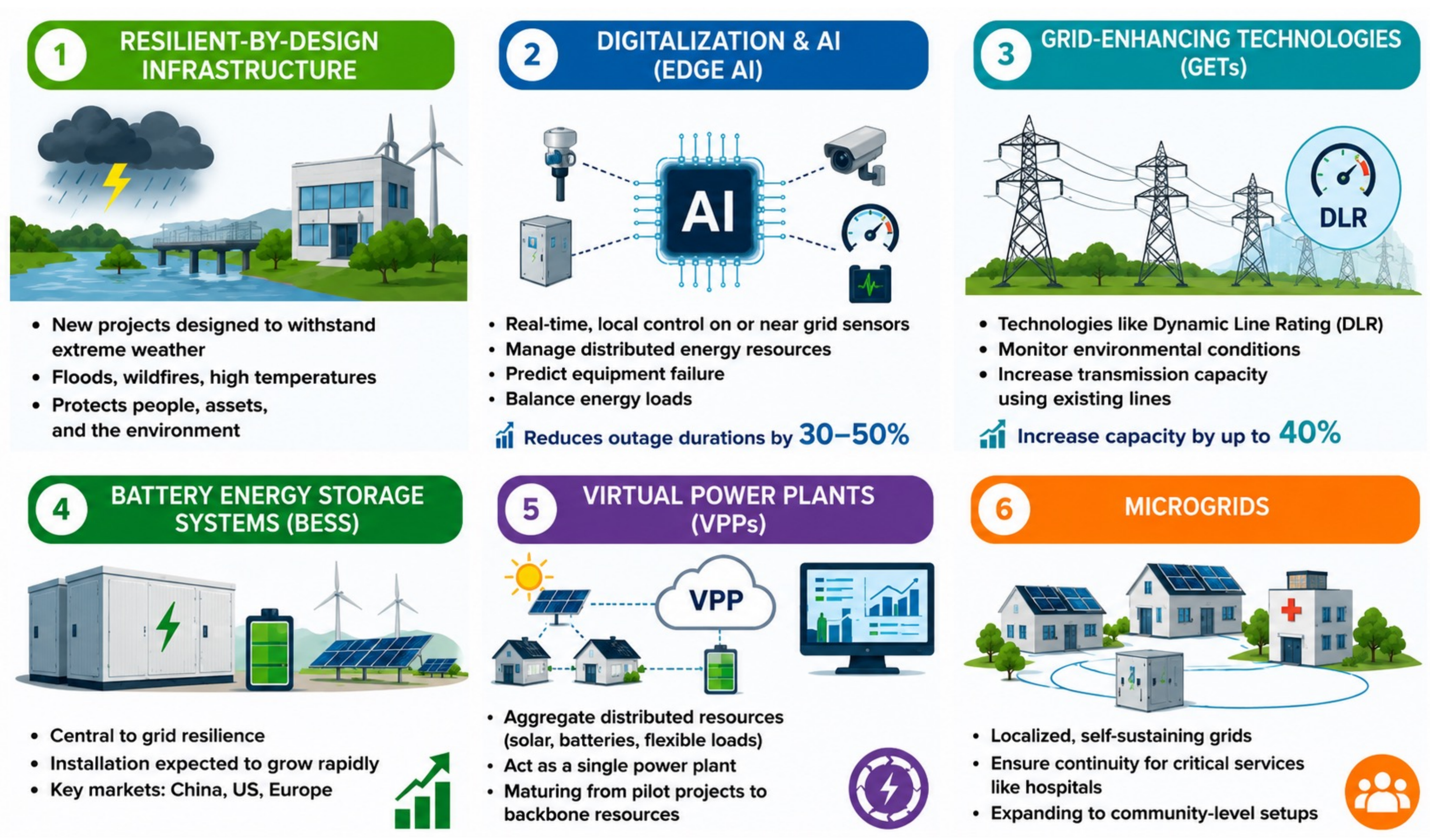

Fig.4 Key Technologies for Enhancing Energy Resilience in Positive Energy Districts

Finally, the Vera Campus at the Politècnica University of Valencia in Spain in moving towards the Net zero emissions and has already succeeded in reducing its electricity consumption by 27.4% from 2021 to 2024, saving over €2.3 million through LEDs, free cooling, improved building envelopes, smart lighting, and 100% renewable energy procurement [12] [13]. In order to design and implement an AI & Machine Learning-based tool to assess Vera Campus flexible energy demand and forecast tool, four forecasting framework — Random Forest Regressor, Gradient Boosting Regressor, XGBoost Regressor and LightGBM Regressor—were tested. The preliminary results showed that the overall forecasting performance of the Global Gradient Boosting Regressor was the best in terms of Mean Absolute Error (MAE).

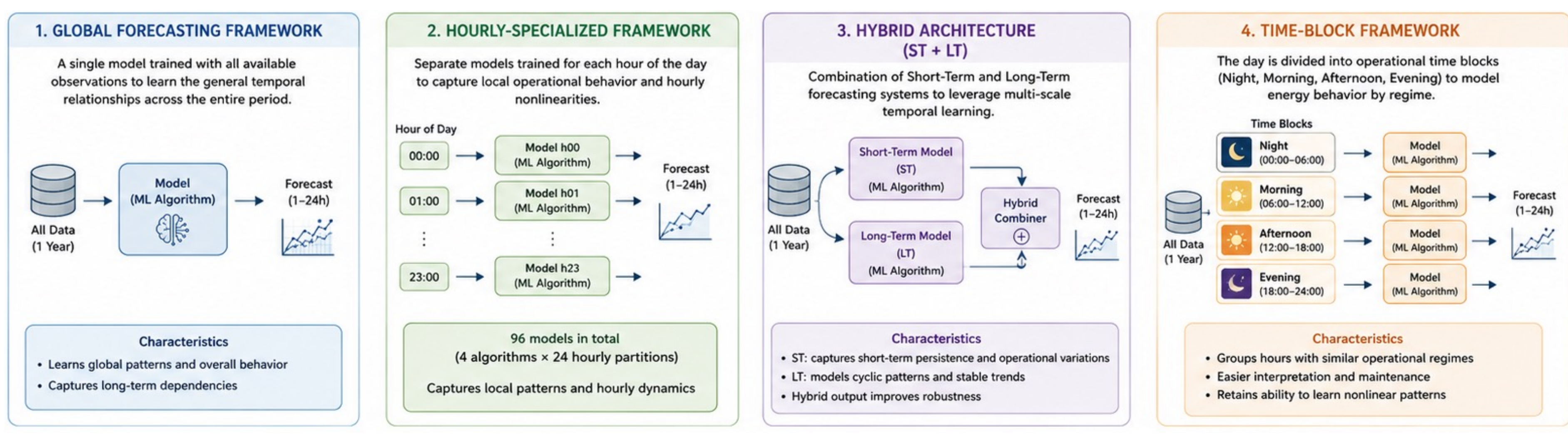

Fig.5 Forecasting architectures explores for energy forecast and efficient management

CONCLUSIONS

This study explores AI's and ML's role in enhancing energy management systems, promoting PED development and identifying solutions to challenges. The holistic conceptualization of a novel approach for PED deployment was carried out. Results shows PEDs can contribute to enhance energy resilience and climate adaptation by integrating resilient by-design high-efficiency buildings, manage local energy flows while adapting existing infrastructure alongside with new solutions. The high initial investments together with the lack of energy planning culture, approved governance models are still barriers to PED deployment Finally, key strategies for Net-zero energy consumption and PEDs deployment have been identified.

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