KỶ YẾU

HỘI THẢO ĐẨY MẠNH GẮN KẾT BA NHÀ
(NHÀ NƯỚC - ĐẠI HỌC - DOANH NGHIỆP)
THỰC CHẤT, HIỆU QUẢ GÓP PHẦN PHÁT TRIỂN ĐẤT NƯỚC
TRONG KỶ NGUYÊN VƯƠN MÌNH

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MỤC LỤC

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HEMS IN FUTURE CITIES: LINKING ACADEMY AND INDUSTRY THROUGH AI

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Abstract – Contemporary residential buildings integrate complex energy technologies but often suffer from suboptimal efficiency. Bridging the gap between academic innovation and market readiness, this paper introduces OPTIM-ON—an AI-driven Home Energy Management System (HEMS) developed through a Triple Helix collaborative framework to maximize self-consumption and minimize operational costs. Utilizing a decentralized Edge AI architecture, the system coordinates PV, batteries, heat pumps, and EV chargers locally. This solution addresses industry demands for seamless retrofit deployment and commercial viability, while simultaneously alignment with public policy goals regarding data privacy, grid independence, and carbon reduction without requiring structural changes.

Keywords – Triple Helix; Energy management systems; Artificial Intelligence; Photovoltaic integration.

1. Introduction

Multi-energy microgrids and advanced energy management systems (EMS) represent cutting-edge solutions for increasing the penetration of renewable energy sources (RES) and managing the growing energy demand of electric vehicles (EVs) [1]. As reported in [2] electricity demand grew more rapidly than both overall energy demand and GDP, increasing by 4.3% in 2024, this represents the largest absolute increase in demand ever recorded. Renewables accounted for the largest share of the growth in total energy supply (38%), followed by natural gas (28%), coal (15%), oil (11%) and nuclear (8%). Global electricity consumption in buildings increased by more than 600 TWh (5%) in 2024, accounting for nearly 60% of total growth in electricity consumption. Key drivers included rising demand for air conditioning, and electrification of some loads traditionally powered by gas (like induction cooktops, heating systems, and electric EV charger). Modern buildings are becoming increasingly complex due to the integration of multi-commodity generation systems (e.g., PV, wind), storage technologies (e.g., batteries, hydrogen), and multiple energy vectors (electricity, heat, mobility) [3]. Addressing this systemic challenge requires a coordinated response within the Triple Helix framework, aligning regulatory sustainability targets with technological innovation and market viability.

Managing these complex systems efficiently is challenging, requiring dedicated control and optimization tools, as well as significant effort in modeling, analyzing, and designing both components and systems. Consequently, EMSs play a critical role in energy system control, especially within grids characterized by high RES penetration. Furthermore, optimization tools rely on accurate load and PV/wind generation profiles to predict from 1 hour to 48 hours in advance the power production but also the load request [4]with the aim to minimize fuel consumption or main grid dependence. Finally, integrating EVs into distribution networks introduces novel challenges that demand new modeling methodologies also considering the request of the final consumer and the cost of energy [5]. In this context, academic research serves as the primary engine for developing these advanced algorithmic frameworks and Artificial Intelligence (AI) solutions to optimize system control, enhance environmental comfort, and ensure operational reliability.

Implementing Artificial Intelligence (AI) can optimize system control, resulting in energy savings, enhanced environmental comfort, and improved system reliability.

The literature features numerous EMS based on statistical methods, some of which incorporate power forecasting tools and AI applications [6], [7]. However, the bridge between laboratory innovation and widespread industrial adoption often falters at end-user acceptance—driven by concerns over personal data privacy—and simplicity of use. To achieve true market penetration, Home Energy Management Systems (HEMS) must be cost-effective, reliable, and easily retrofitted into existing setups without causing structural disruption. By effectively linking the three prongs of the Triple Helix—academic research, industrial scalability, and societal trust—Domopti [8], a spin-off from the Politecnico di Milano [9], delivers a solution that is already an effective market-ready response to these dual technical and socio-economic challenges.

2. The predictive HEMS: OPTIM-ON

In today's context, advanced energy technologies are increasingly being integrated into buildings, including photovoltaic systems, energy storage systems, heat pumps, and charging stations for electric vehicles. This creates a diverse, complex, and rapidly evolving ecosystem. However, simply implementing these technologies does not guarantee optimal utilization. A significant portion of PV energy is often fed into the grid at a significantly lower rate than the electricity price would be a few hours later, rather than being consumed on-site. In most cases, more than half of the energy generated is not used efficiently. Furthermore, investors in energy storage systems often fail to fully exploit their operational potential.

Consequently, AI has become indispensable for energy management in residential buildings. Specifically, this involves the simultaneous, coordinated, automated, and continuous execution of demand forecasting, system management, and cost optimization. While predictive analytics are valuable, they remain isolated data points unless they lead to optimal operational actions. System management is necessary, but without predictive insights into the coming hours, strategic adjustments remain reactive. Finally, cost optimization requires a comprehensive understanding of a building's specific generation and consumption profiles.

Grounded in these principles, DOMOPTI developed an HEMS called OPTIM-ON, that goes beyond reactive EMS by anticipating future scenarios. Through AI, it continuously plans the next 24 hours, processing weather forecasts, energy price fluctuations, and consumption behaviors. Based on this analysis, it optimizes appliance usage, electric vehicle charging, and energy storage allowing also cost save operation. The structure of OPTIM-ON is depicted in Figure 1.

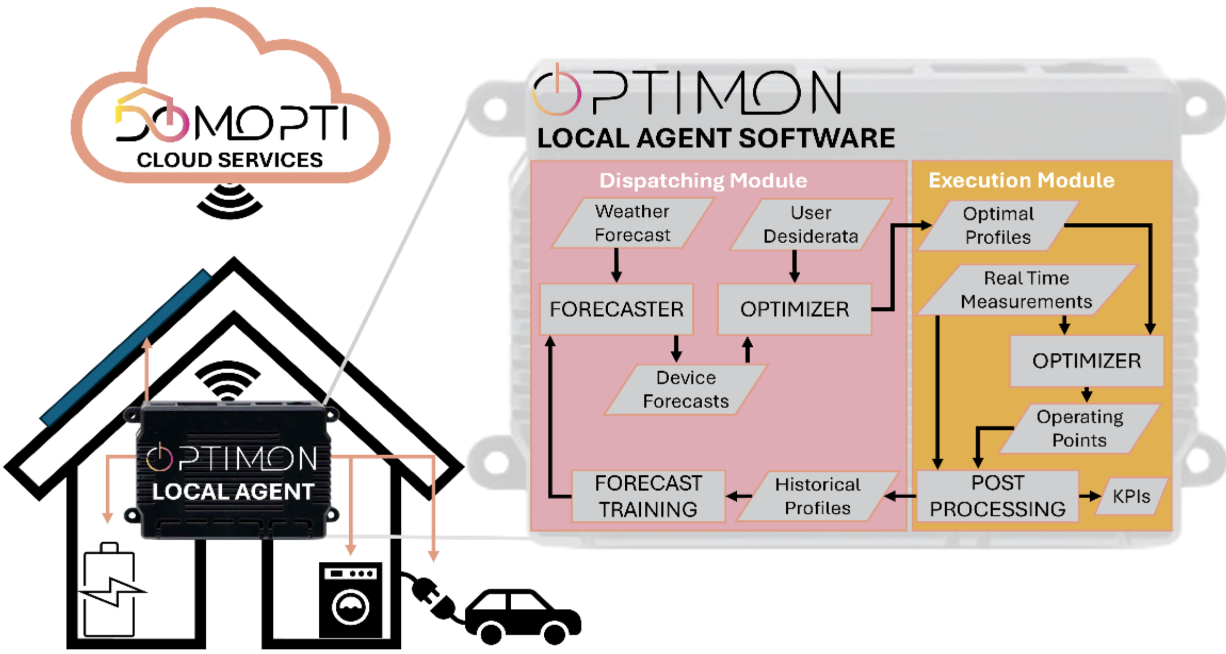

Figure 1. *High-Level schematics of OPTIM-ON*

2.1. Energy costs reduction

As more households adopt PV panels and EVs managing energy efficiently has become a challenge. A recent study [10] has explored how a Smart EMS can optimize home energy use to save money and reduce waste.

The researchers tested a sophisticated two-layer control system on 396 real-world scenarios. In these scenarios homes were equipped with PV panels for energy generation, batteries (BESS) for storage and EVs, testing both standard charging and bidirectional charging (in the so called Vehicle- to-home configuration where the car can actually give power back to the house).

The system works in two steps:

- Planning Ahead: it looks at weather forecasts and energy prices for the next day to create a "strategy".
- Real-Time Action: it makes quick adjustments throughout the day based on what is actually happening.

Using this smart system saved homeowners over 20% on their annual energy costs compared to traditional methods. In some cases, savings reached up to €900 per year. Using an EV as a mobile battery (V2H configuration) added an extra 10–15% in savings. This was even more effective for people who work from home, as the car is plugged in and available more often. The study also shown that buying a dedicated BESS is still not very economically beneficial at current prices, as the smart management of the EV and PV panels provides most of the value.

2.2. Main Features

The main characteristics of OPTIM-ON are the following.

- Harmony and user interaction. OPTIM-ON coordinates PV panels, batteries. EV and smart appliances as a single, integrated system. It maximizes self-consumption during daylight hours and draws power from the grid only when it is most cost-effective. Users define their priorities - the car charged by 7 a.m., the dishwasher finished by dinner - and the system takes care of the rest.
- Privacy. OPTIM-ON is designed to operate fully locally, with computation performed directly within the household. Users may optionally enable secure data sharing with our cloud services. At all times, data ownership and control remain with the end user.
- Compatibility and integration. OPTIM-ON supports leading home automation protocols as well as industrial standards, including Modbus. It interoperates with multi-vendor devices and integrates smoothly with existing infrastructures. Finally, it represents an open ecosystem.

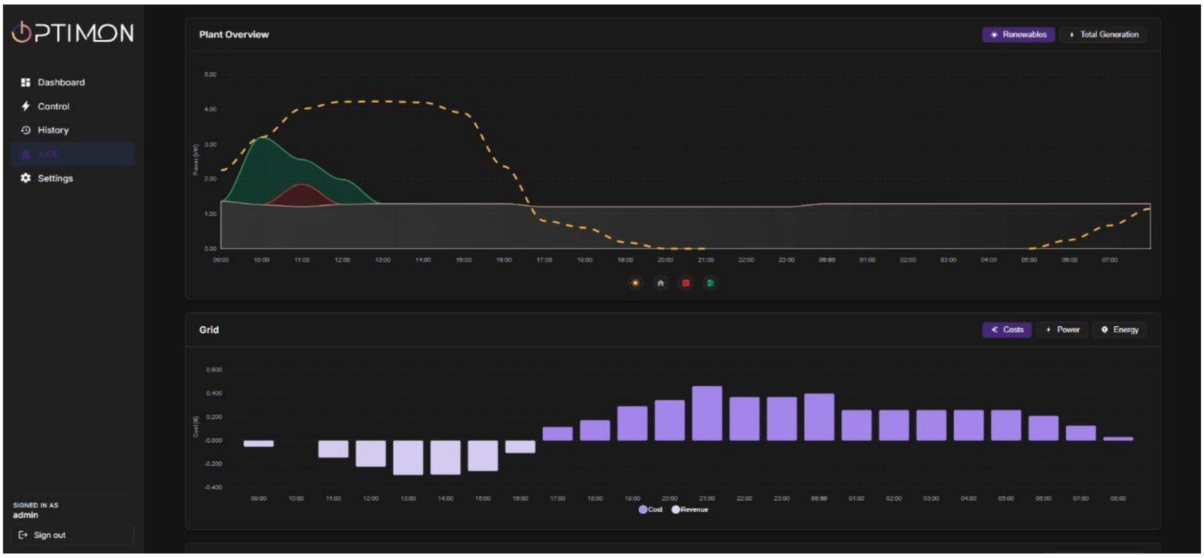

***Figure 2.** Dashboard of OPTIM-ON displaying the optimized 24-hour strategy*

Today, OPTIM-ON focuses on optimizing mainly on PV, BESS, EV, heating system and some households. For future applications, the platform is architected to integrate with energy aggregators, grid services, and Renewable Energy Communities, enabling each home to actively contribute to the electricity system.

2.3. Enabling technology

The operational functionality of a HEMS is contingent upon the communication capabilities between the building's edge devices and the central management software, as reported in Figure 3. Furthermore, if these devices support bidirectional communication - enabling them to receive control commands - the optimization process becomes fully automated.

As mention before, OPTIM-ON is engineered to interface seamlessly with major building automation and industrial communication protocols. This compatibility facilitates retrofit deployment on legacy installations, eliminating the necessity for capital-intensive structural renovations or hardware replacement; an internet connection is the sole prerequisite.

Regarding data ownership and security, OPTIM-ON is deployed on a dedicated, compact hardware gateway connected directly to the local area network, executing all computational processes locally. This Edge AI architecture ensures deterministic system functionality even during network outages (offline operation) while inherently guaranteeing user data privacy.

In conclusion, while contemporary buildings exhibit an increasing density of technological systems, a framework capable of localized cognitive processing and coordinated actuation has been absent. OPTIM-ON addresses this gap, ultimately driving a significant reduction in overall energy consumption and operational costs.

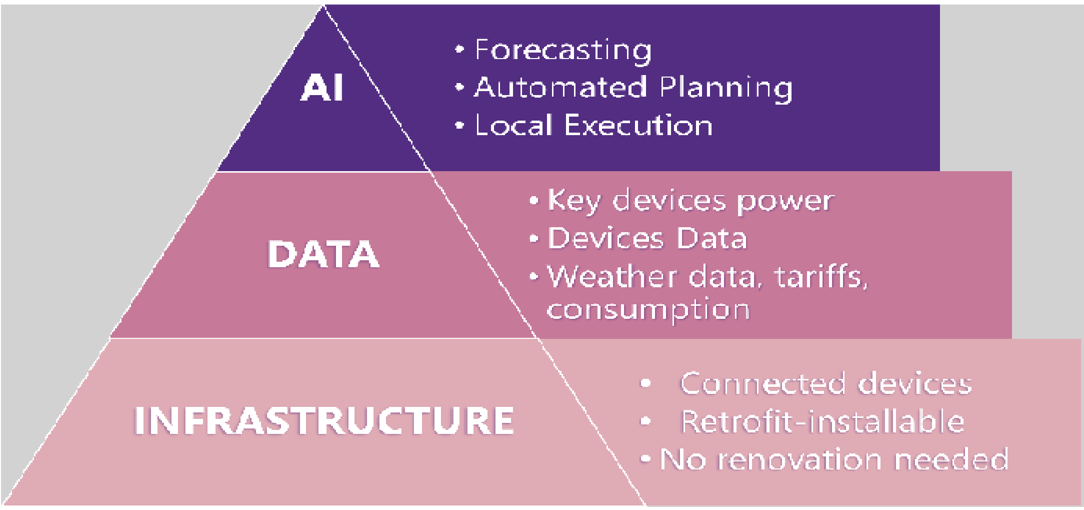

Figure 3. *Pyramid structure of OPTIM-ON*

3. Case of study and results

The proposed system was tested in a real-world deployment on a single-family detached home, equipped with the following components:

- Grid connection: point of delivery limited to 6 kW in import and 6.5 kW in export.
- PV generation: two PV inverters of 3.0 kW and 3.5 kW for a total of 6.5 kW.
- Heating system: heat-pump-only system, consisting of an 11 kW_t heat pump, three thermals
- zones, and one 200 L domestic hot water tank.
- Electric vehicle charging: one single-phase EV charger providing up to 7.4 kW.

Taken together, these components form a residential energy system in which generation, thermal demand, and EV charging must be coordinated within the limits of the grid connection. This configuration provided a realistic and suitably complex environment for evaluating the dispatcher module's ability to balance competing loads, exploit on-site PV generation, and respect both grid and comfort constraints. Notably, every device in this setup can be controlled directly: the setpoints computed by the execution module are sent straight to the respective devices, enabling true online control of the plant.

The electricity prices including transport costs and taxes are reported in Table 1.

Table 1. *Electricity prices of the user case*

	Purchase			Sell
Period	F1	F2	F3	Flat
Week days	08:00-19:00	07:00-08:00 19:00-23:00	23:00-07:00	
Saturday	-	7:00-23:00	23:00-07:00	
Sunday/Holidays	-	-	00:00-24:00	
Value [€/MWh]	286	308	200	100

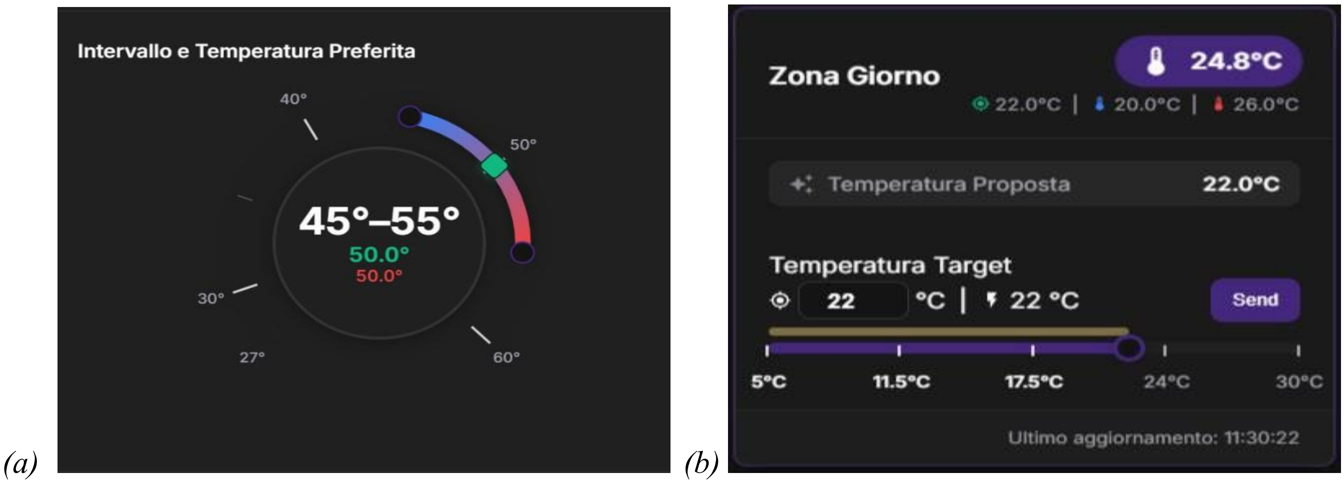

Figure 4. *Interface to control the set-point of (a) the Domestic Heat Water system and (b) the Space Heating system*

Through DOMOPTI's user interface, the user can configure each Thermostat and Domestic Heat water (DHW) component individually, setting a desired temperature target together with an acceptable temperature range around that target, as shown in Figure 4. These settings define the comfort and operational requirements the system must satisfy.

Similarly to the DHW components, the user can set for each Thermostat component at a desired temperature target together with an acceptable temperature range. These settings define again the requirements the system must satisfy for each heating zone.

The system then finds the optimal dispatch of each heating zone depending on:

- Current Zone Temperature;
- Thermal Losses depending on the external temperature;
- Heat Pump COP when in heating mode.

The heat pump integration started in March 2026 and was completed in May 2026. The development period corresponds to midseason without any actual heat need by the user for space heating. Therefore, the results can be limited to the demonstration that the heat pump features were integrated into OPTIM-ON and the system can control the heat pump to minimize the costs. Figure 5 shows a screenshot of the dashboard where the planned operating strategies are reported. The EV is planned to be charged during the night (F3) and when the PV electricity is available. The heat pump is operated between 16 and 18 because it has lower priority than EV car, but take advantage of the cheaper electricity price than the one in F2.

Figure 5. *Planned operating strategies*

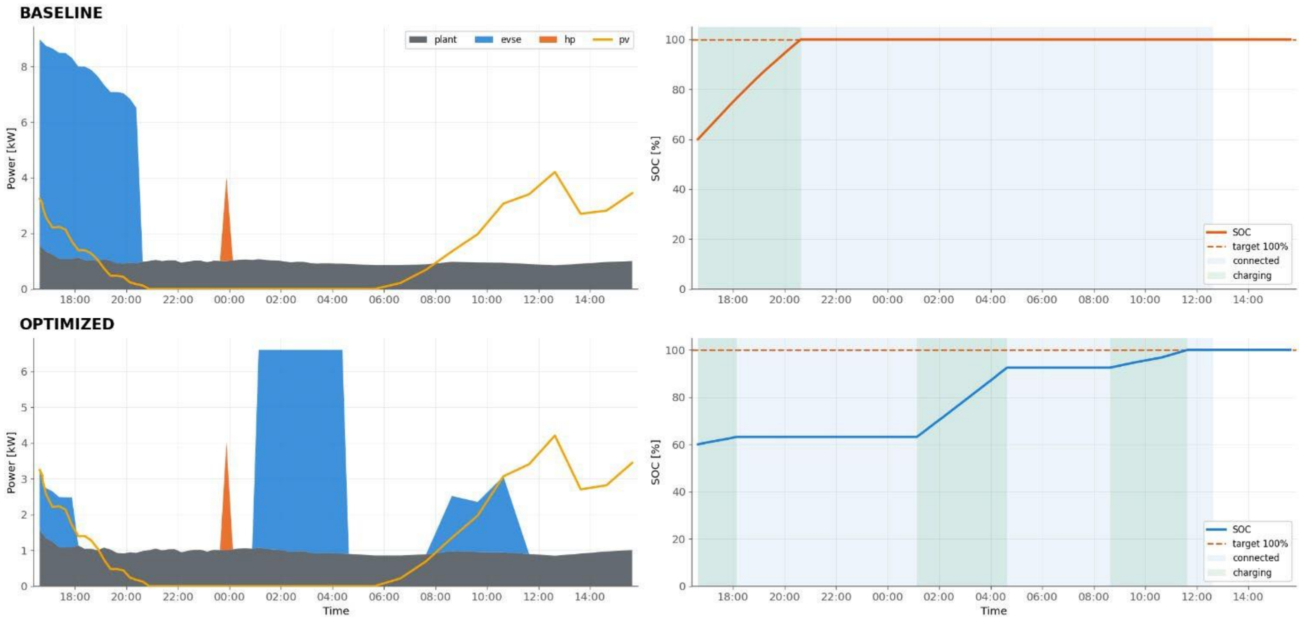

***Figure 6.** Optimized strategy of OPTIM-ON (bottom) versus benchmark strategy (top). Loads (left) and EV state-of- charge (right)*

A comparison between the operating strategy set by HEMS and the one typically used without controlled systems is reported in Figure 6. It is clearly visible the operation of the HEMS which moves the EV charging during nighttime with respect to conventional approaches where the full State-of- Charge (SoC) of the battery is achieved as soon as possible. OPTIM-ON sets the 100% SoC depending on the user need which is at 12:00. In this way, the FV electricity and F3 prices can be exploited. The heat pump request is really limited as consequence of the mid-season case.

Overall, the implementation of HEMS in one day led to 2.5€ savings over 8.90€ which corresponds to 28% savings.

4. Triple Helix Synergy for Sustainable Transition: The OPTIM-ON Case Study

The practical implementation of advanced energy systems exemplifies the Triple Helix model, which integrates government policies, academic research, and industrial commercialization as the primary catalyst for industrial development and technological progress.

In this example, academic research excels in developing high-level mathematical formulations for optimizing multi-energy microgrids, but structured and appropriate technology transfer mechanisms are needed to bridge the gap and achieve industrial market readiness. The development of the OPTIM- ON HEMS predictive system exemplifies this synergy, emerging directly as a commercial solution from Domopti, a university spin-off of the Politecnico di Milano, which adapted academic expertise and offered it in a plug-and-play architecture compatible with multi-vendor protocols.

Another key element is the funding that startups and spin-off can secure from both public and private institutions. Specifically, thanks to the PNRR (Piano Nazionale di Ripresa e Resilienza), the Italian implementation of the EU's Next Generation recovery instrument, DOMOPTI received two grants that enabled the development of its product. The first is a consolidation grant from the MOST - National Center for Sustainable Mobility project t[11], while the second comes from NEST- Network for Energy Sustainable Transition project [12] and is dedicated to developing and implementing several demonstrative case studies requested by third party.

This framework for cooperation between government, academia, and industry is aligned with the core objectives of the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities), while also addressing industry’s need for scalable solutions.

5. Conclusion

Today’s residential energy systems are becoming increasingly complex, characterized by the integration of diverse technologies such as photovoltaic systems, energy storage systems, heat pumps, and electric vehicle charging systems. Studies show that more than half of the energy generated on-site is not consumed directly, leading to inefficient grid-feeding patterns that reduce the economic benefits for end-users and strain public grid infrastructure. To close this operational gap and align industrial readiness with regulatory climate targets, OPTIM-ON was introduced—an innovative, AI-based energy management system for private households. The core scientific innovation of this project is the transition from simple, passive, and reactive energy monitoring to a proactive, automated, and continuous optimization framework. This involves the simultaneous deployment of advanced academic algorithms for demand and generation forecasting, system coordination, and cost optimization.

Furthermore, the proposed architecture overcomes key socio-technical challenges related to market implementation and data security. Thanks to its compatibility with the most prominent communication protocols for home automation and industry, the system enables cost-effective retrofitting of existing buildings without requiring structural modifications—directly addressing market commercialization barriers. By employing a decentralized edge AI approach, data is managed entirely locally, thereby fulfilling stringent public data privacy standards and fostering societal trust.

Ultimately, the realization of OPTIM-ON serves as a prime case study for the Triple Helix model, where the synergy between academia, industry, and government drives tangible progress. The existence of robust institutional frameworks that promote technology transfer and the creation of university spin-offs accelerates industrial and technological deployment. Concurrently, government funding plays a pivotal role in ensuring that cutting-edge academic research findings are seamlessly translated into practical, industrial applications that deliver economic, societal, and environmental value.

REFERENCES

[1] X. Ding, Q. Guo, Ti. Qiannan, K. Jermsittiparsert, "Economic and environmental assessment of multi-energy microgrids under a hybrid optimization technique," Sustainable Cities and Society, vol. 65, 2021, 102630

[2] On-line. https://www.iea.org/reports/global-energy-review-2025/global-trends

[3] S. Polimeni, L. Moretti, E. Martelli, S. Leva, G. Manzolini, "A novel stochastic model for flexible unit commitment of off-grid microgrids," Applied Energy, Vol. 331, 2023, 120228

[4] M. Wood, S. Matrone, E. Ogliari, S. Leva, "Comparing peak electricity load forecasting models for an industrial and a residential building," Mathematics and Computers in Simulation, Vol. 240, 2026, p. 303-316

[5] S. Matrone, E. Ogliari, A. Nespoli and S. Leva, "Electric Vehicle Supply Equipment Day-Ahead Power Forecast Based on Deep Learning and the Attention Mechanism," in IEEE Transactions on Intelligent Transportation Systems, vol. 25, no. 8, pp. 9563-9571, Aug. 2024

[6] O. Omoyele, S. Matrone, et al., "Impact of temporal resolution on the design and reliability of residential energy systems," Energy and Buildings, Vol. 319, 2024, n. 114411

[7] G. Manzolini, A. Fusco, D. Gioffrè, and et al. 2024. "Impact of PV and EV Forecasting in the Operation of a Microgrid" Forecasting 6, no. 3: 591-615.

[8] On-line. https://www.domopti.it/en/

[9] On-line. https://www.polimi.it/en/research/technology-transfer/spin-off

[10] D. Gioffrè, G. Manzolini, S. Leva, R. Jaboeuf, P. Tosco and E. Martelli, "Quantifying the Economic Advantages of Energy Management Systems for Domestic Prosumers with Electric Vehicles", Energies, 2025, vol. 18, 1774

[11] On-line. https://www.centronazionalemost.it/en/start-up

[12] On-line. https://www.energiamercato.it/notizie/enertech/fondazione-nest-call4innovation-2025, in italian

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