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Energy and Cost Optimization of Heat Pump–PV Systems in Retrofitted Multi-Family Residential Buildings

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Abstract:

The ongoing decarbonization of the residential building sector requires replacing conventional heat sources with renewable technologies and developing advanced control strategies for efficient operation. The increasing deployment of heat pumps combined with on-site photovoltaic (PV) systems creates opportunities for reducing operating costs and improving energy demand flexibility. This paper addresses the optimal control of heat pump systems in fully modernized multi-family residential buildings. The analyzed buildings, originally heated by fossil fuels, underwent deep thermal retrofitting. This included building envelope improvements and the subsequent installation of multisource heat pumps, thermal energy storages, and rooftop PV arrays. The study is based on three real multi-family buildings in Poland with comparable characteristics. Crucially, two of these buildings operated during their first post-modernization year relying entirely on a standard rule-based control strategy. This initial period serves as a robust empirical reference case for evaluating the impact of the proposed optimization.

The core of this work is a predictive optimal control strategy designed to seamlessly align the heat pumps electrical demand with the availability of locally generated PV electricity and favorable day-ahead electricity market prices. The strategy utilizes short-term thermal energy storage—specifically water buffer tanks—which provide essential flexibility by physically decoupling heat generation from instantaneous thermal demand. The Model Predictive Control framework employs forecasts of PV generation, electricity prices, and heat demand, enabling proactive scheduling of the compressor instead of reactive control.

The performance is rigorously assessed by comparing key operational indicators before and after implementation. Results clearly demonstrate that predictive control significantly enhances overall building performance. The optimized strategy directly reduced operational costs by approximately 15% and nearly doubled the PV self-consumption rate, increasing it from 33% to 57%. These specific findings highlight that intelligent control and thermal storage are indispensable for maximizing the economic potential of modernized residential energy systems.

Keywords:

Decarbonization; Heat pump; Model predictive control; Photovoltaic systems; Thermal energy storage.

1. Introduction

The global transition toward a sustainable energy future places unprecedented demands on the building sector, which currently accounts for approximately 40% of the European Union’s total energy consumption and 36% of its greenhouse gas emissions [1]. While stringent regulations have successfully minimized the energy footprint of newly constructed buildings, the decarbonization of the existing building stock remains a formidable challenge. This is particularly evident in Central and Eastern European countries, such as Poland, where a substantial portion of the population resides in aging multi-family residential buildings. Historically characterized by poor thermal insulation and a heavy reliance on fossil-fuel-based central heating or individual coal boilers, these structures require immediate and deep energy retrofitting to meet the ambitious climate neutrality targets set by the European Green Deal [2,3].

The paradigm shift in modernizing these multi-family buildings typically involves a two-step approach: first, significantly reducing the thermal demand through envelope improvements (e.g., advanced insulation and high-performance glazing), and second, electrifying the heat supply. Consequently, the integration of high-efficiency multisource heat pumps (HPs) coupled with on-site photovoltaic (PV) generation has emerged as the standard technological pathway for retrofitted residential infrastructure [4,5] . However, the proliferation of HP–PV systems introduce new operational complexities. The inherent intermittency of solar energy creates a temporal mismatch between generation and consumption. In residential buildings, thermal demand typically peaks during the early morning and late evening, directly opposing the midday peak of PV electricity generation. Without intelligent intervention, this misalignment leads to grid congestion, high operational costs, and alarmingly low rates of PV self-consumption [6].

The current technological bottleneck in maximizing the efficiency of retrofitted HP–PV systems is not the hardware itself, but the underlying control logic. Most modernized buildings continue to rely on conventional Rule-Based Control (RBC) strategies [7]. RBC systems operate reactively, modulating the heat pump based on instantaneous feedback loops such as indoor thermostats or outdoor temperature-compensated heating curves. These conventional controllers are inherently short-sighted; they cannot anticipate impending solar irradiance peaks, nor can they react to dynamic, day-ahead electricity market prices. As a result, heat pumps frequently draw expensive, carbon-intensive power from the grid during peak hours, while valuable daytime solar electricity is exported to the grid at sub-optimal tariffs.

To overcome the limitations of reactive control, it is essential to unlock the energy flexibility of the building. This is practically achieved by decoupling the physical generation of heat from its instantaneous consumption through the integration of short-term thermal energy storage (TES), such as water buffer tanks [8]. However, activating this flexibility requires an advanced, proactive control framework. Model Predictive Control (MPC) represents a superior approach, utilizing mathematical models of the system dynamics alongside external forecasts (weather, PV yield, and electricity prices) to optimize the heat pump's operational schedule over a receding time horizon [9,10]. By pre-heating the TES during periods of high PV generation or low electricity prices, MPC shifts the electrical load, effectively utilizing the buffer tanks as a thermal battery.

Despite the extensive theoretical literature highlighting the benefits of MPC for building energy management, a critical research gap persists. The overwhelming majority of current studies are confined to theoretical simulations, idealized virtual environments, or single-family homes [3,11][11, 12]. There is a severe lack of empirical, long-term research investigating the implementation of advanced predictive control in the complex environment of fully retrofitted, multi-family residential buildings. Furthermore, studies that utilize long-term, real-world operational baseline data to quantify the precise economic and energetic value of switching from RBC to MPC in transitional energy markets are exceptionally rare.

Therefore, the primary objective of this paper is to address this gap by evaluating the energy and cost optimization of HP–PV–TES systems supplying fully modernized multi-family residential buildings. The novelty of this study lies in its empirical foundation and longitudinal comparative approach. The research is based on the operation of three real-world multi-family buildings in Poland. Crucially, the study leverages a full year of historical operational data from two of these buildings, which initially ran on a standard RBC strategy. This extensive real-world dataset serves as a highly robust reference baseline. Against this baseline, the paper proposes and evaluates an optimal control strategy designed to proactively align heat pump demand with forecasted PV availability and market price signals. By bridging the gap between theoretical optimization and real-world multi-family retrofitting, this study aims to demonstrate how intelligent control strategies are indispensable for maximizing the economic viability and grid-friendliness of modern residential energy systems.

2. Case study description

2.1. Building characteristics and thermal retrofitting

The empirical basis for this study consists of three multi-family residential buildings located in Poland. These structures are representative of the widespread, standardized housing blocks constructed in Central and Eastern Europe during the late 20th century. Originally, these buildings were characterized by exceptionally poor energy performance, lacking adequate thermal insulation and relying on high-emission, centralized fossil-fuel boilers for space heating and domestic hot water (DHW) preparation [12][13].

To align with contemporary energy efficiency standards and facilitate the transition to low-temperature heating systems, all three buildings were subjected to a comprehensive deep thermal retrofitting process. This modernization primarily targeted the building envelope to drastically reduce heat losses. The interventions included the installation of external wall insulation (Expanded Polystyrene - EPS) and roof insulation. Consequently, the specific space heating demand was reduced to a level that enabled the efficient operation of multisource heat pumps. The generalized characteristics of the buildings are summarized in Table 1.

Table 1. *Case studies description.*

	Building 1	Building 2	Building 3
Location	Central Poland	Northern Poland	Northern Poland
Year built	1989	1987	1981
Net floor area, m^2	3 200	2600	1950
Number of floors	5	5	5
Number of residential units	50	50	40
Scope of the modernization	Heat source retrofitting; building insulation; space heating and cooling; PV	Heat source retrofitting; PV	Heat source retrofitting; PV

2.2. Retrofitted heating and cooling system topology and components

Following the minimization of the thermal load, the conventional heating infrastructure was entirely decommissioned. A decentralized, renewable-based energy topology was implemented. The core heat generation units are cascaded hybrid heat pumps (HP) designed to cover 100% of both the space heating, optional space cooling and DHW loads without the need for fossil-fuel backup heaters. Figure 1 presents the schematic diagram of presented retrofitted system.

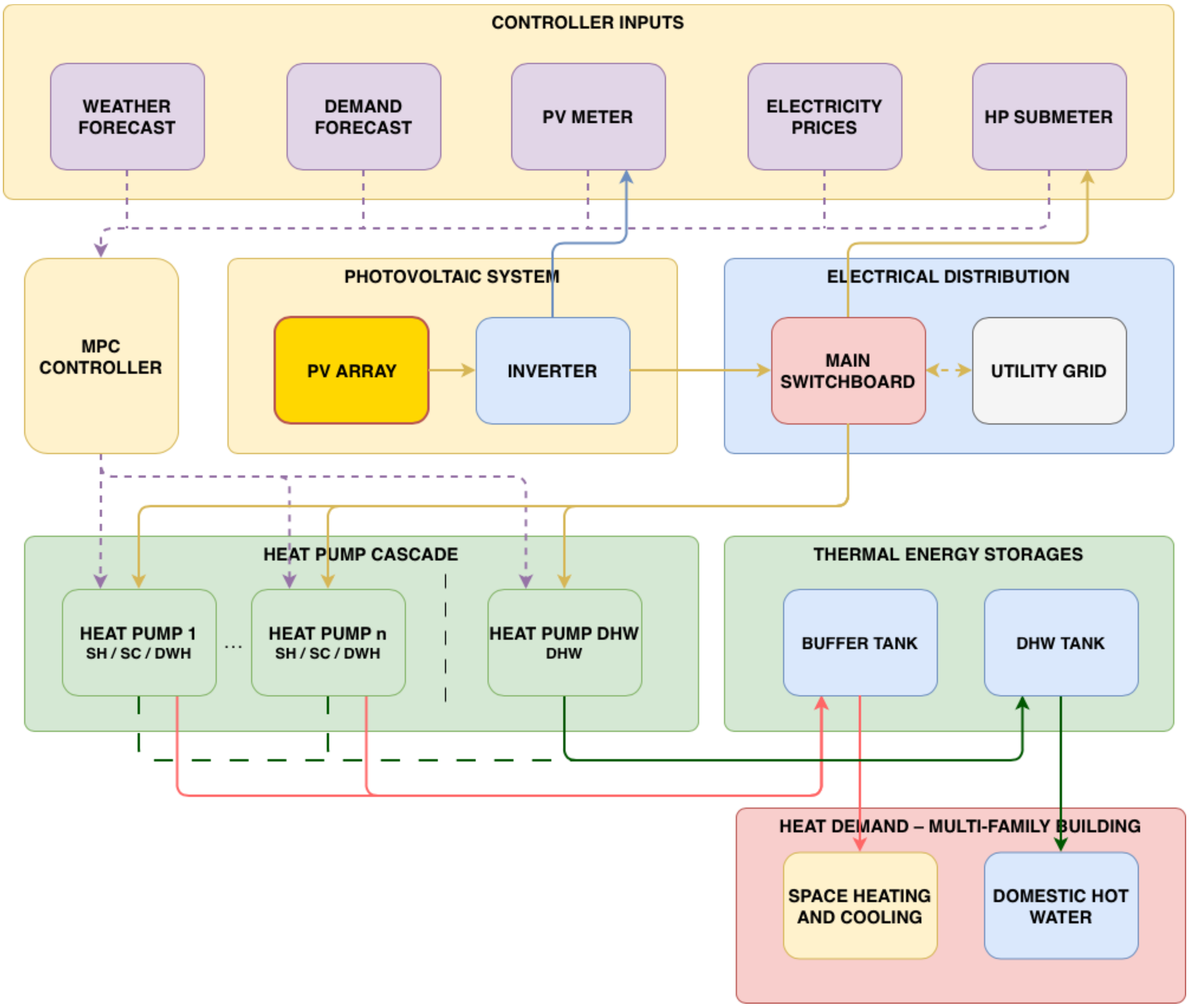

Figure. 1. *Schematic diagram of the retrofitted building energy system with the integrated predictive controller.*

To support the electrical demand of the compressors, rooftop photovoltaic (PV) arrays were integrated into the buildings' microgrids. However, the most critical component enabling the implementation of advanced control strategies is the short-term thermal energy storage (TES). Water buffer tanks were installed to act as thermal batteries. These buffers introduce essential thermal inertia to the system, physically decoupling the heat generation by the HP from the thermal demand of the residential units [13][14]. The technical specifications of the installed energy systems are detailed in Table 2.

Table 2. *Key technical specifications of the modernized energy system components.*

Component	Parameter	Building 1	Building 2	Building 3
Heat pump SH/SC	Number of heat pumps[1]	3	2	2
Heat pump DHW	Number of heat pumps[2]	1	1	1
Space cooling	-	Yes	No	No
BTES	Length of borefield [m]	3600	2800	2800
PV	Installed power peak	65	40	40
Buffer tank	Tank volume m^3	3.0	3.0	3.0
DHW tank	Tank volume m^3	1.5	1.5	1.5
Heating terminal	Delivery system type	Fancoils	Radiators	Radiators

2.3. The reference operation period (Baseline)

A unique aspect of this research is the availability of high-resolution, empirical baseline data. To establish a reliable reference case for evaluating the proposed optimization framework, Building 1 and Building 2 were continuously monitored over a full 12-month period immediately following their modernization i.e. from November 2022 and June 2023 respectively.

During this reference period, the systems were governed by a standard Rule-Based Control (RBC) strategy, which represents the industry default for such installations [14][15]. The RBC logic was purely reactive: the space heating setpoints were dictated by an outdoor temperature-compensated heating curve (ranging from 30 °C to 55 °C for both buildings), while the DHW setpoints were maintained within rigid upper and lower hysteresis limits (45 °C and 50 °C respectively).

The analysis of this reference period revealed significant operational inefficiencies. The RBC algorithm operated blindly with respect to external dynamic variables. It frequently activated the heat pumps during the early morning and late evening to satisfy peak occupant demand—hours that unfortunately coincide with the highest grid electricity tariffs and zero solar irradiance. Conversely, during the midday solar peaks, the buffer tanks were often already fully charged from nighttime operation, leaving no thermal capacity to store the "free" PV electricity. This temporal misalignment resulted in a substantial portion of the generated PV energy being exported to the grid, yielding a low self-consumption rate of merely 33%. This baseline clearly underscores the necessity of implementing predictive optimization to unlock the flexibility provided by the TES.

3. Optimization framework and control strategy

3.1. Predictive control concepts

The fundamental limitation of standard Rule-Based Control (RBC) is its inherent reactivity. To fully exploit the energy flexibility of the retrofitted buildings and the installed thermal energy storage (TES), this study implements a Model Predictive Control (MPC) strategy. The MPC architecture relies on continuously solving a constrained optimization problem over a receding time horizon.

The predictive controller integrates multiple forecasting data streams: local weather predictions (ambient temperature and solar irradiance), anticipated building heat demand profiles, and dynamic day-ahead electricity market prices [15][16]. Based on these inputs, the algorithm proactively schedules the operation of the heat pump compressor over a 24-hour horizon. The primary intent is to maximize the self-consumption of the on-site PV generation and avoid compressor operation during peak electricity tariff periods, all while strictly adhering to predefined thermal comfort boundaries.

3.2. Objective function formulation

The primary objective of the optimization framework is to minimize the total operational expenditure (OPEX) associated with grid electricity consumption over the prediction horizon N. Since the local PV generation

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[1] Nominal heating capacity and COP at B0/W35: 53.3 kW, 4.44

[2] Nominal heating capacity and COP at B0/W35: 18.6 kW, 4.65

directly offsets grid demand, the objective function F is formulated as the minimization of electricity purchasing costs, expressed mathematically in Equation (1)

$$F = min \sum_{t=1}^{N} \left[P_{grid}(t) \cdot c_{elect}(t)\right] \cdot \Delta t, \qquad (1)$$

where:

$P_{grid}(t)$ is the electrical power drawn from the utility grid at time step t in kW,

$c_{elect}(t)$ is the spot market electricity price at time step t in PLN/kWh,

Δt is the duration of the time step in h,

N is the prediction horizon (e.g. 24 steps for daily horizon).

3.3. Thermal Energy Storage (TES) dynamics

The short-term thermal energy storage (buffer tank) is the critical component providing system flexibility. The thermodynamic state of the TES is governed by the discrete-time energy balance shown in Equation (2):

$$E_{TES}(t+1) = E_{TES}(t) + \left(\dot{Q}_{HP}(t) - \dot{Q}_{dem}(t) - \dot{Q}_{loss}(t)\right) \cdot \Delta t, \qquad (2)$$

where:

$E_{TES}(t)$ is the thermal energy accumulated in the buffer tank at time t in kWh,

$\dot{Q}_{HP}(t)$ is the heating capacity supplied by the heat pump in kW,

$\dot{Q}_{dem}(t)$ is the forecasted building heat demand (space heating and DHW combined) in kW,

$\dot{Q}_{loss}(t)$ represents the standing heat losses from the tank to the ambient environment in kW,

Δt is the duration of the time step in h.

The state variable (tank temperature) is subject to strict physical and operational constraints, defined by inequality (3):

$$T_{min} \le T_{TES}(t) \le T_{max}. \qquad (3)$$

The lower bound T_{min} guarantees the maintenance of occupant thermal comfort, while the upper bound T_{max} is dictated by the technological limits of the heat pump compressor. In the MPC algorithm, allowing the temperature to reach T_{max} enables the "overheating" of the buffer during periods of high PV yield, effectively converting the water tank into a virtual battery.

3.4. Operational constraints and power balance

The thermal output of the heat pump depends on the electrical power consumed by the compressor and the Coefficient of Performance (COP). The COP is a highly non-linear function dependent on both the source temperature $T_{source}(t)$ and the supply temperature of the heating system[16] [17]. This relationship is defined in Equation (4):

$$\dot{Q}_{HP}(t) = P_{HP}(t) \cdot COP\left(T_{source}(t), T_{TES}(t)\right). \qquad (4)$$

To correctly determine the grid power draw ($P_{grid}(t)$) the algorithm calculates the electrical power balance of the building at each time step, as shown in Equation (5):

$$P_{grid}(t) = \max\left(0, P_{HP}(t) + P_{load}(t) - P_{PV}(t)\right), \qquad (5)$$

where $P_{load}(t)$ is the baseline electrical demand of the building (unrelated to heating) and $P_{PV}(t)$ is the forecasted power generated by the photovoltaic array. The "max" function implies that any surplus PV energy exported to the grid does not generate direct revenue that would offset current operational costs within the formulated cost-minimization scheme.

3.5. Implementation of MPC control

The developed Model Predictive Control (MPC) strategy was physically deployed and validated in the monitored buildings. Real-time operational data, including thermal energy storages temperatures and actual PV generation and baseline electrical demand of the building, were collected at one minute resolution and aggregated to the hourly time step (Δt). External data streams, specifically the day-ahead electricity prices from the Polish Comodity Exchange (TGE) and local high-resolution weather forecasts, were retrieved automatically through an API.

The optimization problem was solved every hour on a dedicated cloud server, and the resulting optimal setpoints for the heat pump thermal power and TES charging rates were transmitted back to the local Programmable Logic Controllers via the MQTT protocol. The local controllers were responsible for the low-level execution of these setpoints, managing system hydronic and compressors. This in-situ implementation allowed for a direct empirical evaluation of the MPC's performance under real-world conditions, such as unpredictable occupant behaviour and sensor noise, distinguishing this study from purely numerical simulations.

4. Results and discussion

The implementation of the Model Predictive Control (MPC) strategy was evaluated against the baseline established during the first year of operation under standard Rule-Based Control (RBC). The comparative analysis focuses on two primary performance indicators: the reduction of operational expenditures (OPEX) and the enhancement of photovoltaic (PV) self-consumption through thermal load shifting.

4.1. Thermal comfort and system reliability

Before analyzing the economic and energetic gains, it is imperative to note that the optimization framework successfully maintained the required thermal comfort levels within the retrofitted buildings. Throughout the evaluated predictive control period, the indoor temperatures and the domestic hot water (DHW) supply temperatures consistently remained within the strict boundaries defined by the constraints of the optimization algorithm (as formulated in Section 3). The thermal inertia of the modernized building envelope, combined with the capacity of the water buffer tanks, provided sufficient buffering to prevent any noticeable temperature drops during the periods when the heat source intentionally deactivated by the MPC.

4.2. PV self-consumption, load shifting and operational cost reduction

The most direct economic benefit of transitioning from reactive to predictive control is the substantial reduction in operational costs. The analysis of the billing data and system logs revealed a reduction in total electricity purchasing costs of approximately 15% compared to the RBC reference case.

This financial optimization was not achieved by reducing the overall thermal energy delivered to the building—as the thermal demand remained relatively constant for similar weather conditions—but rather through strategic load shifting. Under the baseline RBC, the heat pump frequently engaged during the morning (06:00–09:00) and evening (17:00–21:00) peaks to satisfy immediate occupant demand. Unfortunately, these periods correspond precisely to the highest dynamic electricity tariffs.

Conversely, the MPC algorithm utilized the day-ahead price signals to map the most cost-effective operational windows. By pre-charging the Thermal Energy Storage (TES) during off-peak night hours or utilizing free solar electricity during the day, the system was able to completely shut down the compressor during peak-price periods. The 15% cost reduction demonstrates that software-driven optimization can yield significant financial returns without requiring any additional capital expenditure (CAPEX) on physical infrastructure.

The most profound systemic improvement was observed in the interaction between the heat pump and the local PV generation. In retrofitted multi-family buildings, the temporal mismatch between solar yield and heating demand is a critical bottleneck. During the reference year, the RBC system yielded a PV self-consumption rate of only 33%. Most of the generated solar energy (67%) was exported to the grid at unfavorable rates, as the buffer tanks were not prepared to absorb the midday energy surge.

The implementation of the predictive framework radically altered this dynamic, increasing the PV self-consumption rate to 57%—a near doubling of local energy utilization. The hourly distribution of PV yield and its self-consumption for each building is presented in Figure 2. This 24-percentage-point increase is a direct result of the controller's ability to forecast solar irradiance.

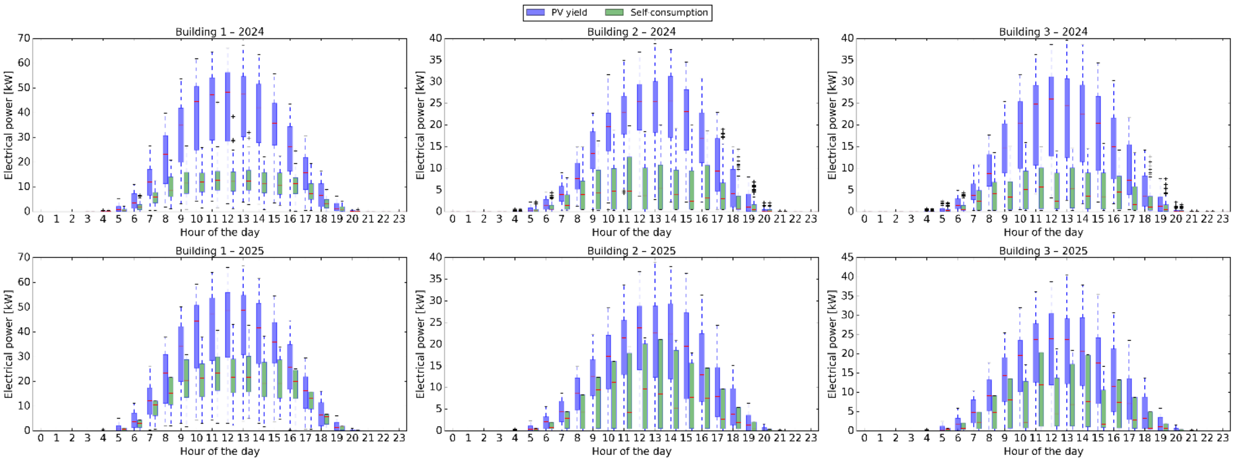

Figure. 2. *Improvement in the PV self-consumption rate achieved through thermal load shifting.*

On days with forecasted high solar yields, the MPC deliberately allowed the buffer tank temperatures to drop slightly during the early morning, avoiding grid power consumption. As the PV generation ramped up toward midday, the algorithm forced the heat pump to operate at maximum capacity, utilizing the "free" solar electricity to overheat the TES up to its maximum technological limit (T_{max}). This process effectively transformed the excess electrical energy into stored thermal energy. By the time the evening thermal demand peak occurred, the building could draw entirely from the fully charged buffer tanks, leaving the heat pump inactive. Figure 3 presents daily operational profile in November.

This shift in self-consumption not only improves the economic viability of the PV installation but also provides a crucial service to the broader electrical grid by and reducing evening grid congestion.

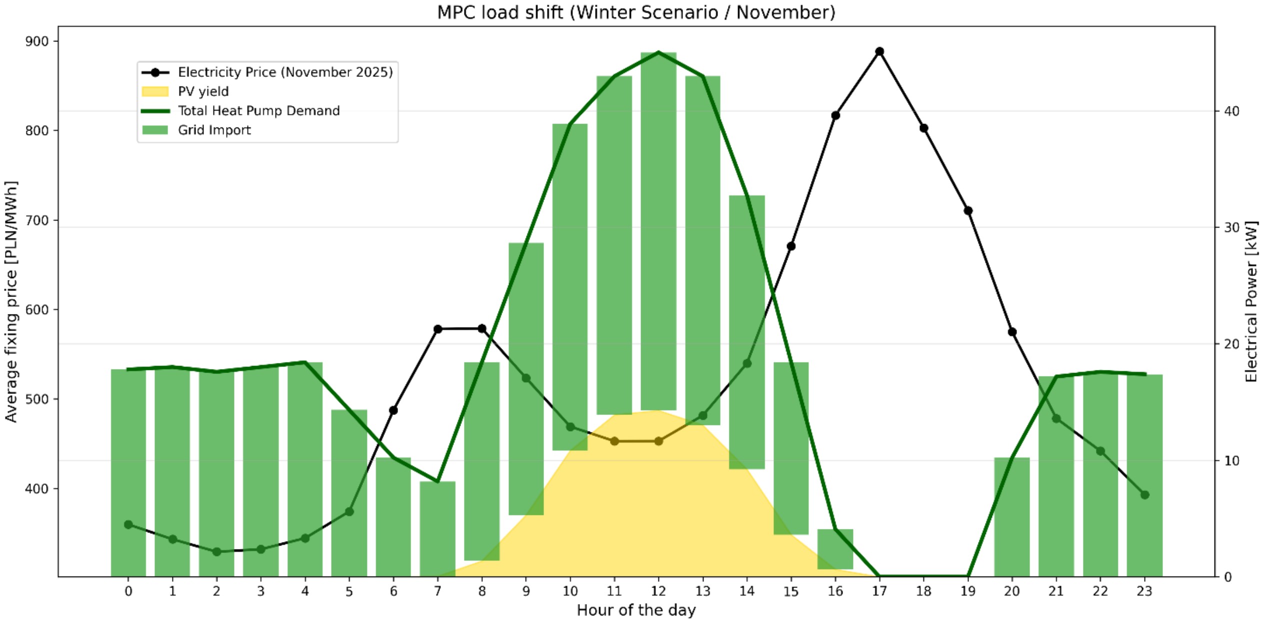

Figure. 3. *Daily operational profile demonstrating the thermal load shifting mechanism: utilizing PV generation to overheat the buffer tank during midday.*

5. Conclusions

The deep thermal retrofitting of existing multi-family residential buildings is a cornerstone of the European decarbonization strategy. However, as demonstrated in this study, the mere installation of renewable hardware—such as heat pumps and PV arrays—is insufficient to maximize economic and energetic efficiency.

This paper presented an empirical evaluation of an optimal control strategy implemented in fully modernized multi-family buildings in Poland. By transitioning from a standard, reactive Rule-Based Control (RBC) to an advanced Model Predictive Control (MPC) framework, the study highlighted the critical role of software in modern energy systems. Based on the comparative analysis against a full-year reference baseline, the following main conclusions can be drawn:

- OPEX Reduction: Proactive scheduling of the heat pump compressor, driven by dynamic electricity price forecasts, led to a 15% reduction in operational costs. This proves that intelligent control is a highly cost-effective measure for retrofitted buildings.
- Maximization of Local Renewables: The predictive algorithm successfully mitigated the temporal mismatch between solar generation and heating demand. By anticipating midday solar peaks and utilizing the thermal energy storage as a virtual battery, the system increased the PV self-consumption rate from an initial 33% to 57%.
- The Necessity of Thermal Storage: The results underline that short-term thermal energy storage (buffer tanks) is an indispensable enabling technology. Without the physical thermal inertia provided by the TES, the MPC would not have the necessary flexibility to shift the electrical loads.

Ultimately, these findings contribute to a broader understanding of residential energy management. They demonstrate that optimized control strategies are essential for transforming passive, energy-intensive residential blocks into flexible, low-emission, and cost-efficient nodes within the future smart grid.

Nomenclature

P	electrical power, kW
Q	heating capacity, kW
E	thermal energy, kWh
T	temperature, ºC
c	spot market price, PLN/kWh
N	prediction horizon, h
COP	coefficient of performance, -
DHW	domestic hot water
SH	space heating
SC	space cooling
BTES	borehole thermal energy storage

Subscripts and superscripts

PV	photovoltaics
HP	heat pump
TES	thermal energy storage
$elect$	electricity
dem	demand
$grid$	national grid
$loss$	losses
$load$	baseline load
$source$	heat pump source

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