

Optimizing Energy Consumption in Buildings

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Abstract – The optimization of hybrid building energy systems is commonly addressed using two main approaches: model-based and rule-based energy management strategies that ensure operational stability, and heuristic or algorithmic methods designed to optimize multiple objectives such as operational cost, CO₂ emissions, and system reliability. However, these approaches are often insufficiently validated with respect to energy demand sensitivity, limiting their robustness under dynamic and uncertain operating conditions. This study proposes an integrated energy forecasting and management framework that combines real-time energy management with intelligent load control based on dynamic building energy modelling. Despite significant progress in hybrid renewable energy system control, existing solutions frequently lack unified and computationally efficient algorithmic architectures capable of simultaneously addressing multiple renewable energy sources, energy storage systems, and demand response. Moreover, many approaches exhibit limited effectiveness in handling complex multi-objective optimization problems in real-time applications. To overcome these limitations, the proposed framework integrates machine learning-based energy demand forecasting with a two-level optimization strategy supported by adaptive parameter control and parallel evaluation. The framework enables real-time decision-making while maintaining computational efficiency. By coordinating hybrid renewable energy systems with conventional power supply infrastructure, the proposed approach reduces carbon emissions and energy consumption while ensuring occupant comfort, thereby demonstrating strong potential for practical deployment in smart and energy-efficient buildings.

Keywords – Building energy mode; building energy; building dynamic simulation; PMV.

1. INTRODUCTION

Problems related to inefficient energy use are a global concern and addressing them is an integral part of sustainable development, which integrates environmental, economic, and social considerations and shapes resource-use requirements. Buildings account for over 40% of total energy consumption and one-third of greenhouse gas emissions. One of the European Union's key objectives is to reduce primary energy consumption in response to ongoing climate change.

With growing attention to energy efficiency, this share remains significant due to increasing comfort standards and rising household demands. Improving the energy performance of

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buildings primarily involves reducing the minimum energy requirements for heating, cooling, and domestic hot water preparation, which constitute the main components of building operating costs.

Given current trends in assessing building energy performance, it is essential to consider the impact on energy consumption across all elements of the system: heat source – distribution networks – building technical systems – occupants – building envelope. Further improvements in the thermal insulation properties of building envelopes are reaching diminishing returns.

Therefore, efforts to reduce building energy consumption are increasingly shifting – alongside the integration of renewable energy sources – toward improving and optimizing the operating modes of building technical systems. This approach must ensure the rational fulfilment of user needs and promote conscious occupant behaviour. Further research will enable the evaluation of renewable energy efficiency using both energy and exergy approaches, taking into account the required level of thermal comfort defined by relevant standards and applying models that incorporate human thermoregulation mechanisms.

Thus, energy consumption for indoor comfort accounts for a significant share of global energy demand [1]–[5]. This primarily includes energy used for space heating, domestic hot water preparation, and ventilation [6]–[8]. The level of energy consumption is also influenced by rapid urbanization, population density, climatic conditions, building characteristics, and socioeconomic factors [9]–[12].

As society and energy-consuming technologies continue to evolve, overall energy demand is expected to increase, while the negative consequences of excessive energy use remain unresolved [13]–[17]. Therefore, it is essential to recognize that energy consumption is intrinsically linked to global challenges, requiring a balance between economic growth and environmental responsibility. Understanding energy consumption patterns constitutes the first step toward developing efficient and sustainable energy systems and reducing the ecological footprint [18]–[21].

The implementation of energy-efficient technologies, optimization of heating and air-conditioning systems, application of advanced materials, improved thermal insulation, and integration of renewable energy sources are effective measures for reducing energy consumption and should be applied in a comprehensive manner [22], [23]. Automated control of energy supply systems enables the adjustment of energy demand in response to price signals. Consequently, an optimal solution for residential energy systems involves the use of hybrid energy sources, energy storage systems, and distributed energy resources, which also facilitates the efficient integration of renewable energy sources [24]–[26]. Energy modelling provides a systematic framework for analysing the complex interactions among energy sources, their optimization, and the influence of various factors on overall energy consumption. Mathematical and engineering models of energy use offer a structured and comprehensive approach to investigating these issues [27]–[29].

Although numerous studies have examined building energy efficiency using various modelling techniques, the development of integrated approaches that account for the multiple factors influencing energy consumption remains a significant challenge. In this paper, we present the results of energy consumption modelling conducted for a newly constructed energy-efficient academic building at the Kielce University of Technology. The study applies cause-and-effect modelling approaches capable of capturing complex interactions among the various factors affecting energy consumption.

Building simulation tools such as *EnergyPlus*, which was also employed in this study, enable the development of dynamic models of overall building energy performance and facilitate comprehensive analyses of energy-intensive heating systems. Despite the

substantial advancement of such tools, they remain subject to limitations related to input data quality and model assumptions [30]–[32].

Furthermore, interactions among energy systems may not be fully represented, potentially leading to inaccuracies in simulation results [33], [34]. Thermal comfort standards are typically based on adaptive models derived from data obtained through simultaneous measurements of environmental parameters and occupants' thermal responses. Thermal conditions are commonly assessed using the Predicted Mean Vote (PMV) index, which is a function of six variables. Four of these, according to ISO 7726, are objective environmental parameters: air temperature, air velocity, relative humidity, and mean radiant temperature.

Using this approach, the present study analyses the impact of energy-efficient heating operation modes on both energy consumption and the PMV index through dynamic modelling. In addition, energy consumption levels are optimized and predicted using machine learning techniques.

2. DEVELOPING AN ENERGY MANAGEMENT STRATEGY

The research hypothesis assumes that achieving near-zero-energy buildings requires a comprehensive analysis of the building as a complex energy system, combining mathematical modelling with field experiments. This study focuses on the efficient utilization of both renewable and conventional energy sources through the improvement and optimization of the operating modes of building technical systems while maintaining thermal comfort conditions.

The key research tasks include the development of dynamic models of building energy processes, comparison of measured and modelled energy consumption data, and investigation of the combined operation of renewable and conventional energy sources using physical and mathematical modelling approaches.

Local building automation systems employ integrated energy models that incorporate renewable energy sources, enabling the optimization of energy use and enhancement of overall building energy performance. These technologies extend beyond basic energy management by providing real-time control, monitoring, and automation of building systems, including heating, cooling, and lighting. By applying advanced algorithms and machine learning techniques, energy models can predict consumption patterns and enable dynamic control of energy storage and energy use components. Modelling plays a crucial role in shaping our understanding of energy use strategies and provides a systematic framework for analysing the complex interactions among factors influencing building energy consumption. Dynamic models enable the development of optimal resource allocation scenarios and the design of hybrid energy supply systems.

The planning and configuration of such energy systems are performed using multi-objective optimization algorithms. The operating parameters of each subsystem are calculated in real time to achieve the objectives of minimizing energy consumption and operational costs. Hybrid energy sources perform multiple functions—including heating, ventilation, air conditioning, and lighting—and interact through coordinated optimization mechanisms that prevent adverse effects of local control strategies on overall system efficiency.

For example, when energy consumption forecasts indicate an impending peak load period, the planning system prioritizes adjustments to the heating system and reduces non-essential lighting loads to alleviate system stress. Furthermore, the control strategy incorporates real-time feedback to continuously update operating parameters. Planning accuracy is progressively improved through dynamic optimization, enabling rapid responses to load fluctuations and precise control of energy consumption. This planning approach ensures a dynamic balance between efficient energy system operation and occupant comfort

requirements by integrating real-time monitoring, predictive modelling, and multi-objective optimization based on energy cost and availability. Such prioritization minimizes overall energy consumption while maintaining required comfort levels. System efficiency is further enhanced by selecting energy sources that operate at the highest efficiency under varying demand conditions.

2.1. Object of Research

The development and validation of an energy consumption model were carried out for the existing energy-efficient, smart, renewable energy-based teaching and laboratory building *ENERGIS* at the Kielce University of Technology. The design concept of the *ENERGIS* building (Fig. 1) envisioned a highly energy-efficient facility comprising classrooms and research laboratories equipped with advanced technologies aimed at minimizing energy consumption. The building integrates teaching and laboratory functions and includes 22 rooms, office spaces, specialized laboratory equipment, renewable energy systems, intelligent building management systems, as well as heat exchange and heat recovery installations.

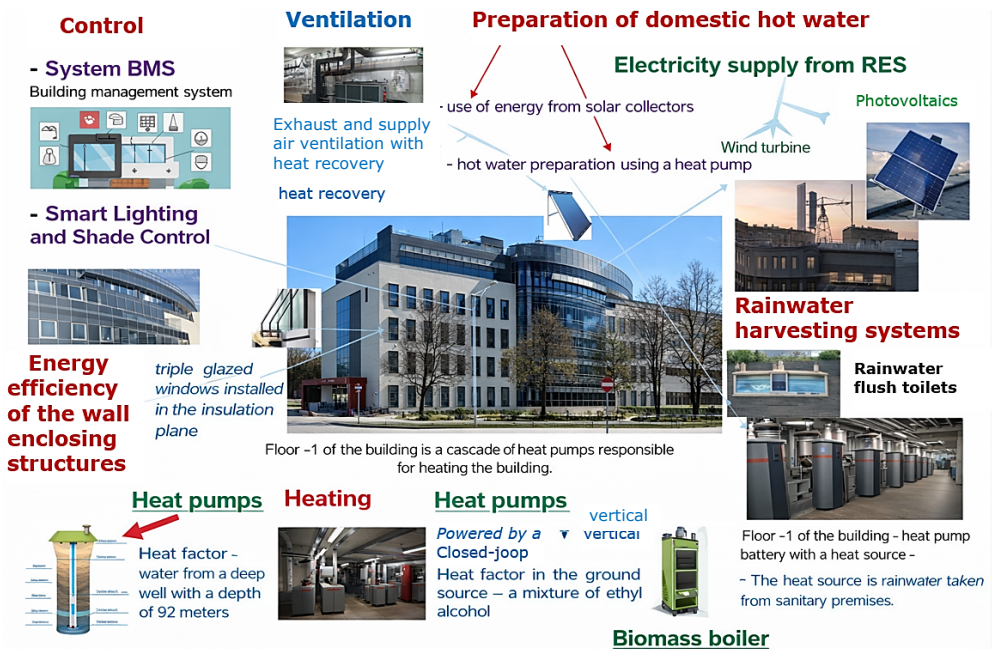


Fig. 1. The *Energis* building.

The building exemplifies intelligent, energy-efficient, and sustainable design. It has a total floor area of 5121.24 m² and consists of four above-ground floors and two underground levels.

- The facility incorporates the following renewable energy systems:
- solar thermal collectors for domestic hot water production,
- photovoltaic panels and a 5-kW wind turbine supplying selected lighting circuits in corridors and stairwells,
- heat recovery from a glazed façade chamber,
- four heat pumps extracting thermal energy from a working fluid circulating through sixteen vertical geothermal boreholes.

To enhance overall sustainability, a rainwater harvesting and recirculation system was implemented. In addition, variable refrigerant flow (VRF) heat pump units were installed as an alternative and complementary energy source.

Heat recovery from the glazed chamber is integrated within the four-story, semi-circular, south-facing glass façade. Solar radiation heats the air in the cavity between the semi-circular outer façade and the inner flat glazing. The heated air is subsequently extracted, and the recovered thermal energy is stored and utilized within the building's energy system. The building is equipped with advanced renewable energy technologies and is classified as "intelligent" due to the comprehensive monitoring and control of its engineering systems via a Building Management System (BMS). The building's energy systems were investigated as part of the research project entitled "Improving the Efficiency of Building Energy Systems in Existing Urban Areas" (Grant No. DEC-2025/57/B/ST8/01347). However, the present article reports only the results of the initial testing phase of the newly developed energy management strategy.

The energy consumption model focuses on two thermal zones located on the second floor, situated on the south and north façades, respectively. Although the floor areas of the analysed rooms are identical, the glazing ratio differs significantly: windows account for 30 % of the wall area on the north façade and 68 % on the south façade. This configuration enables substantial solar heat gains on the southern side. To prevent overheating during periods of excessive solar radiation, external blinds installed on the south-facing windows (see Fig. 1) regulate solar gains. On the north side, additional heat can be supplied through the glazed façade chamber. The building is planned to operate under a controlled heating strategy, the parameters of which will be determined through dynamic modelling.

2.2. Energy Consumption Modelling

To study the building, a dynamic simulation model of two thermal zones was developed using the *EnergyPlus* software. The heating system is based on heat pump technology. The simulation employs hourly climate data from the IWEC international weather file for Kielce, provided in the "EPW" format to ensure seamless integration with the *EnergyPlus* simulation model.

Thermal comfort was evaluated using the following subjective parameters: clothing thermal resistance $I_{clo} = 0.155 \text{ m}^2 \text{ }^\circ\text{C/W}$ and metabolic rate $M = 58 \text{ W/m}^2$.

The analysis was conducted for second-floor rooms divided into two zones – southern and northern – with identical areas (374 m^2) and building envelope structures. The southern zone receives additional thermal energy from solar radiation, which was incorporated into the simulation model. Fig. 1 illustrates that heating energy consumption during the winter months differs by 10–15 % between the northern (Mon) and southern (Sd) zones. During the warmer months of the heating season, this difference increases to 20–25 % due to additional solar gains in the southern part of the building.

The application of intermittent heating strategies results in a further reduction in heat consumption, reaching up to 12 % over the entire heating season. Specifically, energy savings amount to approximately 10 % during the winter period and up to 15 % during the off-season. For a detailed analysis of hourly load fluctuations, two representative months were selected: December, representing the cold period with low solar radiation, and November, representing the off-season (Fig. 2).

The one-time significant reductions in heating load observed in south-facing rooms (Fig. 2) are attributed to surges in solar radiation. In Fig. 2(b), frequent scheduled heating interruptions are evident during the warmer months of the heating season. Analysis of these data enables the strategic planning of temperature setpoint reductions during non-occupancy

periods and weekends without compromising thermal comfort. A portion of the surplus energy can be stored, and additional energy accumulation is achievable through solar gains in the glazed collector, for example, at hours 48, 144, and 420 in December. In November, similar opportunities for energy accumulation exist with an even greater effect, reflecting typical patterns during transitional periods of the year.

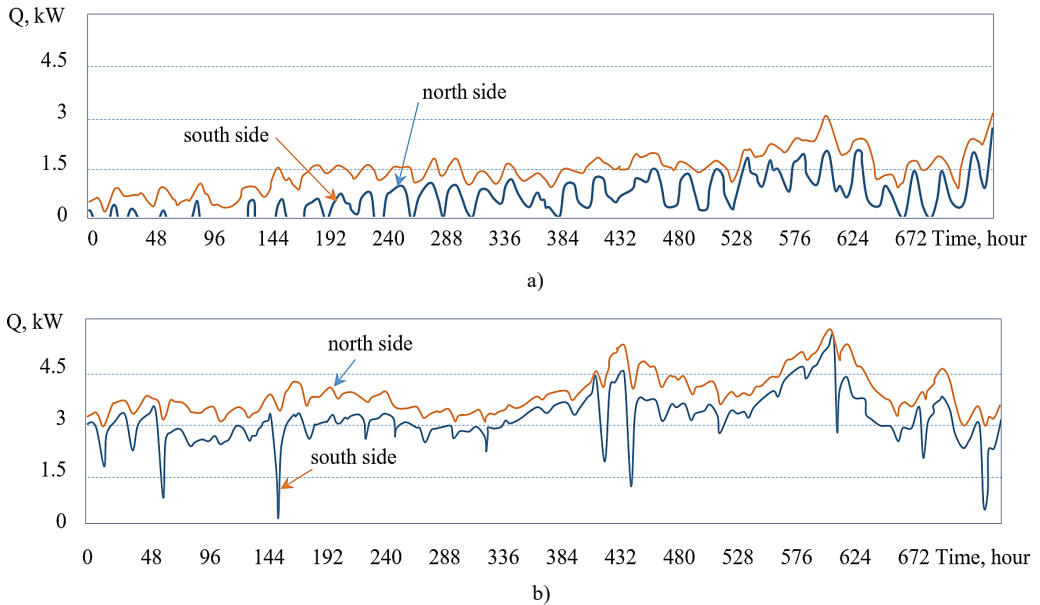


Fig. 2. Thermal load on the heating system in the studied premises for November (a) and December (b).

3. THERMAL COMFORT INDEX

3.1. Exergic Assessment of the PMV Parameter

In accordance with the international standard EN ISO 7730, the minimum exergy consumption of the human body, the corresponding air temperature, and the Predicted Mean Vote (PMV) index were determined. The input parameters used in the model for this analysis are summarized in Table 1.

TABLE 1. DATA FOR CALCULATION

Parameter	Units of measurement	Meaning
Relative humidity	%	40
Atmospheric pressure	Pa	101 325
Thermal insulation of clothing in summer	$\text{m}^2\text{K/W}$	0.124
Thermal insulation of clothing in winter	$\text{m}^2\text{K/W}$	0.155
Metabolism	W/m^2	58
Mechanical work	W/m^2	0

To estimate the PMV parameter, the components of the exergy balance of the human body were calculated for the conditions of Table 1, using the methodology presented in the study [35].

The structure of the exergy output flows changes when the ambient conditions and microclimate parameters in the room change. In the studied rooms, the temperature was set at 20–22 °C regardless of the season. But on the south side due to solar radiation, according to the BMS records of the house, the temperature can reach 26 °C and then air conditioning should be turned on. If for summer conditions the main share of the exergy output flow falls on the consumption by the human body (about 70 %), then for winter conditions – on the radiation exergy – 50 %, and on the consumption of exergy by the human body – only 40 %. This is explained by the greater difference between the temperature of the skin surface and the ambient environment if the air temperature is increased. The increase in the absolute value of convective and radiative heat transfer in the balance causes a decrease in the share of exergy consumption by the human body. When the temperature increases, the response of the energy system may be to use automated blinds, or to turn on air conditioning at a certain stage. Fig. 3 illustrates the dependence of human exergy consumption on the mean radiant temperature and air temperature within the rooms. The graphs represent different values of the room's mean radiant temperature. At low air temperatures, exergy consumption is elevated. As the air temperature increases, exergy consumption reaches a minimum, after which it rises again due to evaporative cooling of the skin surface.

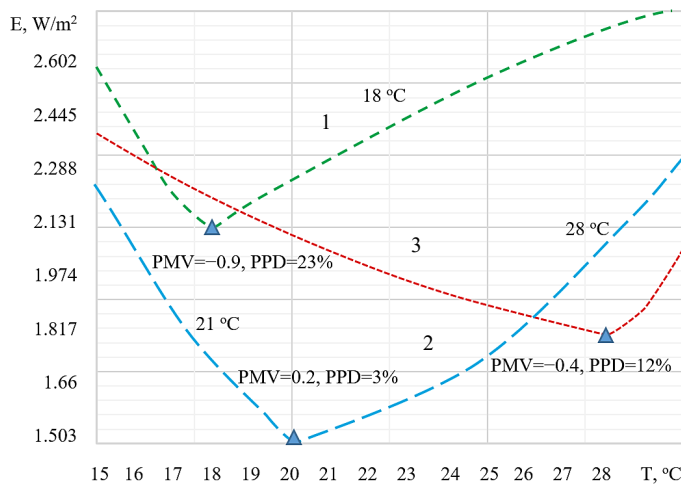


Fig. 3. Dependence of the exergy value on the air temperature for different values of the radiation temperature: 1–18 °C; 2–20 °C; 3–28 °C.

For the points corresponding to minimum exergy consumption, the PMV and PPD indices were evaluated. PPD, the predicted percentage of dissatisfied occupants, along with PMV, represents the primary indicators of human thermal sensation according to the international standard EN ISO 7730. The PMV values were found to range between –0.4 and 0.5. The minimum exergy consumption may correspond to a PMV of 0.2; however, in this analysis, the exergy reference temperature was assumed equal to the room air temperature. During the warm period of the year, convective and radiative heat exchanges from the human body surface are relatively insignificant compared to other components, due to the small

temperature difference between the skin surface and the surrounding air. Consequently, the contribution of human exergy consumption to the overall energy balance increases compared to winter conditions. In our assessment, the minimum exergy consumption criterion provides a more appropriate indicator of thermal efficiency than the Predicted Mean Vote, as defined by EN ISO 7730.

3.2. Thermal Comfort in the Studied Premises

The study was conducted for the working hours of the heating season in representative rooms with external walls oriented to the north and south, employing energy-saving heating strategies. PMV was calculated exclusively for these working hours. The human thermal comfort index (PMV) in educational institutions is a critical factor influencing occupant health and productivity. The PMV index predicts the average level of thermal comfort for occupants within a given space. A PMV value of 0 represents ideal thermal comfort, whereas values above +1 or below -1 indicate conditions that are clearly unacceptable for most occupants. The acceptable thermal comfort range is generally considered to be $-0.5 < \text{PMV} < +0.5$.

Maintaining high indoor air quality in educational spaces is particularly important for enhancing student learning outcomes. Ventilation requirements have increased over time due to updated building codes, stricter hygiene standards, and growing awareness of the impact of indoor air quality on occupant health. Consequently, regular assessments of thermal comfort in educational facilities are essential to identify potential issues and implement adjustments necessary to maintain optimal environmental conditions.

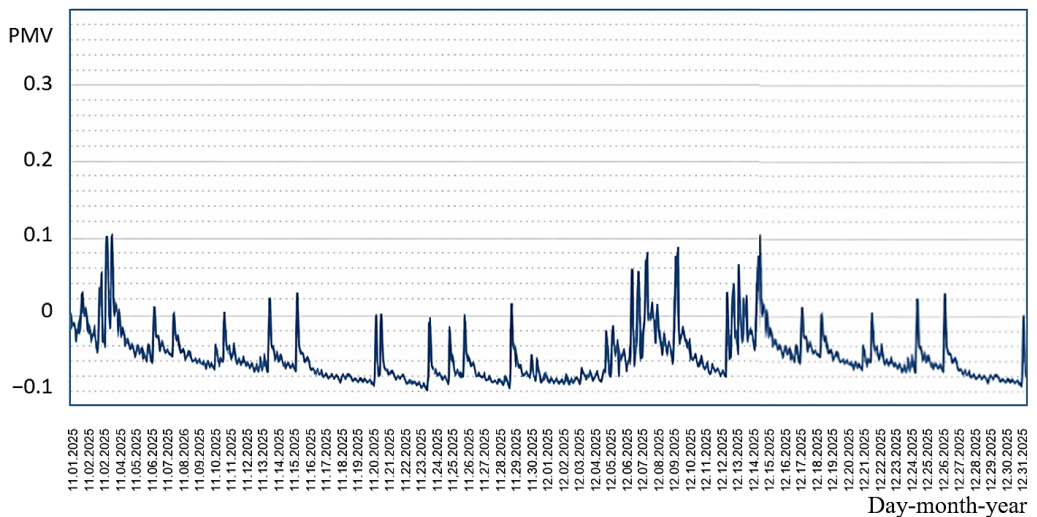


Fig. 4. PMV values for the heating period during working hours from 8:00 to 20:00 for rooms with a south orientation without regulation.

Fig. 4 presents the predicted variation of PMV during the working hours of the heating season for rooms with south-facing external walls, without regulation of the energy supply system. Similar calculations were performed for the north-facing walls. During the winter months, the average PMV is approximately 0.1. Peak PMV values are observed for the southern orientation due to solar heat gains.

The implementation of energy-saving heating strategies, which reduce air temperature by 3 °C during non-working hours, does not result in a significant decrease in PMV. However, the application of intermittent heating strategies allows for an average reduction in energy consumption of approximately 16 % during the winter period. Interestingly, PMV fluctuations in the off-season are predominantly positive for the northern orientation, whereas for the southern orientation, they can be negative. In addition, for the southern-facing rooms, distinct PMV peaks occur throughout the cold period during periods of direct solar radiation.

4. DYNAMIC POWER MANAGEMENT

EnergyPlus software provides reliable predictions of building energy consumption and occupant comfort. However, achieving high levels of forecast accuracy requires substantial computational resources. To address this limitation, machine learning techniques, including artificial neural networks (ANNs), were employed to estimate building energy performance with improved computational efficiency and accuracy. In this study, the building energy balance computed in *EnergyPlus* served as the primary physical model. MATLAB was used to develop the artificial neural networks. A recurrent neural network (Long Short-Term Memory, LSM) was selected to predict building energy demand. The objective of the training process is to minimize the mean squared error between the predicted output sequence and the corresponding actual values in the training dataset. The LSM model is primarily designed to predict room temperatures and the associated heating energy demand over the study period. Actual temperature data were collected and logged by the Building Management System (BMS), providing reference data for model training, validation, and forecasting. A single LSM network was applied to predict hourly heating demand, rather than using separate models for fixed temperature setpoints. This approach enables the model to account for dynamic setpoint changes rather than being limited to static values. The selected temperature range (18 °C, 20 °C, and 25 °C) reflects practical operational conditions: temperatures below 20 °C may cause discomfort, whereas temperatures above 20 °C may exceed acceptable thermal conditions. To enhance the efficiency of the heating system and minimize PMV deviations, an optimization function was employed to ensure that heating demand forecasts accurately follow dynamic setpoint changes while maintaining thermal comfort. The system optimization also incorporates solar radiation per unit area of the southern-facing rooms and indoor and outdoor temperatures from one hour prior to the forecasted period. It should be noted that building energy consumption is influenced by numerous factors beyond those considered in this simulation. For example, accurate occupancy estimation is critical for precise energy demand forecasting, as accounting for room occupancy hours is necessary to incorporate internal heat gains.

For training the LSM artificial neural network, input and output data generated in *EnergyPlus* were imported into the MATLAB platform. The analysed dataset covers 61 days (November and December), including scenarios with continuous operation of the energy system as well as planned heating interruptions. This two-month period – from November 1 to December 31 – yields a total of 7200 data points, representing various scenarios and their impact on energy consumption. To improve forecasting accuracy, all input variables were normalized to a 0–1 scale. These variables include outdoor air temperature, indoor air temperature, previous-hour heating demand as a function of time, and solar radiation (time-dependent). The selection of these inputs accounts for the thermal mass of the building spaces. In future work, an assessment of the impact of occupancy will be incorporated into the model; this is expected to be straightforward for an academic building. However, this factor was not included in the results presented in the current study.

Considering the building's thermal mass, which stores and releases heat in response to setpoint changes, the model inputs were configured to capture these dynamics. Key input variables include indoor and outdoor air temperatures, previous heating demands (up to one hour prior), dynamic setpoint changes, and associated temporal functions. This input configuration allows the LSM network to accurately model the influence of thermal mass on heating demand under varying setpoint conditions.

Once the Pareto set was identified (Fig. 5), the appropriate optimization criterion needed to be selected. In this study, the PMV index was prioritized, meaning that the forecast focused on maintaining the desired comfort level, while aiming to improve the building's energy efficiency. Alternatively, it is also possible to identify solutions that minimize energy costs while limiting deviations in PMV.

Fig. 5 and Fig. 6 present the forecasted conditions for December 25th in north-facing rooms, which corresponded to the coldest day of the analysed period (Fig. 2). Blue dots indicate optimal setpoint temperatures that track the outdoor temperature trend (solid line). Implementing this scenario is predicted to reduce heating costs by approximately 12 %, while maintaining comfort levels corresponding to a PPD of 12 %.

The recommended optimal scenario incorporates a higher setpoint temperature between 5:00 and 7:00 AM to account for relatively low outdoor temperatures during this period. As the outdoor temperature rises later in the day, the setpoint gradually decreases. Considering the building's thermal inertia, a relatively constant indoor temperature of 20–21 °C is maintained, which, as shown in Fig. 3, corresponds to $PMV \approx 0.2$ ($PPD \approx 3\%$).

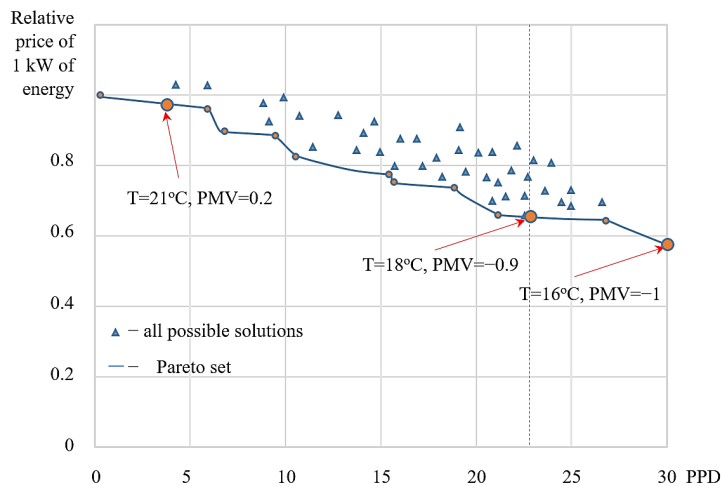


Fig. 5. Pareto graph for optimizing energy supply of selected premises.

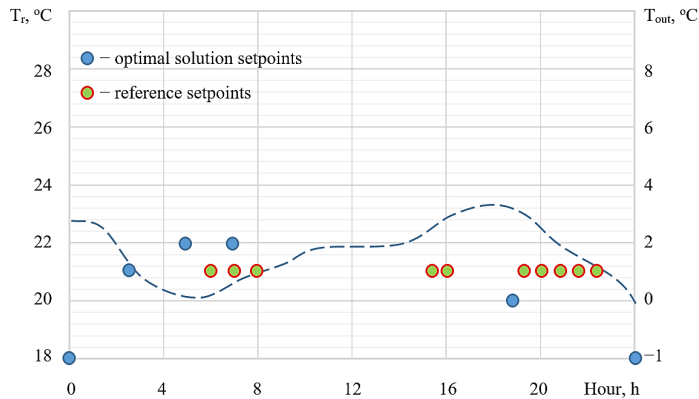


Fig. 6. Predicted temperatures for December 25.

5. CONCLUSION

This article presents a comprehensive approach to improving energy efficiency in green buildings, integrating dynamic energy consumption modelling, intelligent scheduling, multi-objective optimization, and forecast adjustment. Experimental results demonstrate that this approach effectively enhances building energy efficiency, improves coordination of building systems, and optimizes resource allocation. However, the computational complexity and initial performance of the algorithm still require further improvement.

A study of building energy consumption and the thermal comfort index (PMV) was conducted for representative rooms with external walls oriented to the south and north, under energy-saving heating modes based on a dynamic energy model developed in *EnergyPlus*.

The implementation of intermittent heating strategies led to reductions in heating energy consumption of up to 12 % over the entire heating period. For the winter period specifically, savings reached approximately 10 %, while during the off-season, reductions of up to 18 % were observed. Intermittent heating not only reduces heating demand but also mitigates negative PMV deviations, maintaining comfort within the acceptable range (−0.5 to 0.5). In south-facing rooms during the off-season, additional reductions in heating demand are possible while still preserving permissible PMV values.

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