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Total Performance in Practice: Energy Efficiency in Modern Developer-Built Housing

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Abstract

Improving the energy efficiency of residential buildings is essential for achieving global climate goals and reducing environmental impact. This study analyzes the Total Performance approach using the example of a modern semi-detached house built by a Polish developer, as an example. The building is designed with integrated systems that minimize energy consumption while maintaining resident comfort. The building is equipped with an air-to-water heat pump, underfloor heating, mechanical ventilation with heat recovery, and automatic temperature control systems. Energy efficiency was assessed using ArCADia–TERMOCAD 8.0 software in accordance with Polish Technical Specifications (TS) and verified by monitoring real-time electricity consumption during the heating season. The results show a PED from non-renewable sources of 54.05 kWh/(m^2·year), representing a 23% reduction compared to the Polish regulatory limit of 70 kWh/(m^2·year). Real-time monitoring conducted from December 2024 to April 2025 confirmed these results, indicating an actual energy demand of approximately 1771 kWh/year. Domestic hot water (DHW) preparation accounted for the largest share of energy consumption. Despite its dependence on grid electricity, the building has the infrastructure to enable future photovoltaic (PV) installation, offering further potential for emissions reduction. The results confirm that Total Performance strategies are not only compliant with applicable standards, but also economically and environmentally viable. They represent a scalable model for sustainable residential construction, in line with the European Union's (EU's) decarbonization policy and the goals of the European Green Deal.

Keywords: total performance; energy efficiency; heat pump; sustainable construction

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1. Introduction

The construction sector is currently one of the largest consumers of energy and natural resources, responsible for over 40% of global energy consumption and approximately 33% of carbon dioxide (CO_2) emissions [1,2]. In particular, the residential building stock contributes significantly to these figures, especially in heating, cooling, and domestic hot water (DHW) demands [3]. Additionally, the production of building materials such as cement, steel, and glass generates another 11% of emissions, making the built environment among the most carbon-intensive industries [4]. In the context of accelerating urbanization and the increasing demand for housing, improving energy efficiency in residential construction becomes a foundation stone of the global climate mitigation [5]. The United Nations

Sustainable Development Goals (SDGs), particularly SDGs 7, 9, 11, 12, and 13, clearly highlight the need for zero-emission buildings and the energy transformation of cities (Figure 1). Hafez et al. [6] pointed out that the main challenges for the sector include both technological and social aspects, as well as the lack of uniform assessment methods and gaps between expected and actual energy effects. This confirms the need for an integrated and comprehensive approach, as represented by the Total Performance concept.

Figure 1. SDGs related to energy efficiency and sustainable housing.

The concept of Total Performance broadens the traditional idea of energy efficiency by integrating energy consumption, environmental impact, user comfort, and building durability throughout its life cycle (LC). For modern developers, this implies designing residential buildings, especially detached and semi-detached homes, that not only comply with current regulations but also ensure compliance with both current and future environmental and energy regulations [5,7,8]. In the context of this study, the concept of Total Performance encompasses not only energy consumption but also occupant comfort, operational costs, environmental impact measured via CO_2 emissions, and the building's readiness for future technological upgrades. For clarity, in the rest of this article, "Total Performance" will be used as a comprehensive approach, integrating both energy and non-energy aspects, in line with the Life Cycle Assessment (LCA) approach and the EU's sustainable construction goals. This holistic approach differs from traditional frameworks like LCA or the Nearly Zero Energy Buildings (NZEB) standard by explicitly integrating real-time operational data, user behavior, and flexibility for future improvements. Total Performance encompasses both design-related aspects, such as building orientation, insulation quality, envelope airtightness and operational elements (actual energy use, thermal comfort, and embodied emissions). Digital technologies (e.g., Building Information Modeling (BIM), Structural Health Monitoring (SHM) sensors, energy monitoring) now enable continuous tracking and optimization of these parameters [7,9].

One of the sector's key challenges is the so-called "performance gap", which is the divergence between the energy performance that was designed and the energy performance that is actually achieved. In recent years, more and more studies have emphasized the importance of that phenomena. Post-occupancy evaluations, which take into account the impact of actual conditions of use and residents behavior on energy consumption, are particularly important here. Studies such as [10–12] show that even with advanced construction and installation technologies, without the appropriate involvement of users and monitoring of system performance, there may be significant deviations from the assumed energy parameters. Taking these aspects into account in research on the energy efficiency of buildings allows for a more complete understanding of the actual impact of technology, design, and use on energy consumption. Energy Performance Certificates (EPCs) often rely on static simulations and fail to account for user behavior, execution errors, or unplanned retrofits [1]. In residential buildings, this discrepancy can lead to unexpected operating costs and lower occupant satisfaction. Hafez et al. [6] mentioned that this gap was identified as one of the most serious barriers to the implementation of energy efficiency in construction. The authors point to the lack of measurement standards, the underestimation of the impact of the end user, and the limitations of EPC methods as the main causes of the problem. Reliable evaluation allows for understanding the root causes of these deviations and improving future investment strategies [5,10,13].

In the context of Central and Eastern Europe, Mišík et al. [14] emphasize that despite the growing number of studies on energy efficiency in this region, the potential for building modernization, particularly in terms of thermal insulation and heating systems, remains largely untapped. They also point to the slow pace of implementation of integrated modernization strategies and the poor representation of housing stock in energy research agendas. The literature provides examples of the use of artificial intelligence (AI), including artificial neural networks (ANN), for predicting energy consumption at an early stage of design, particularly in the context of public and commercial buildings. Although these methods are currently less commonly used in single-family housing analyses, their further development could provide a potential tool to support the Total Performance approach on a larger scale of investment [2,15,16]. Modern residential developments increasingly feature integrated energy systems with rooftop photovoltaic (PV), battery storage, heat pumps, and electric vehicle (EV) charging infrastructure, operating similarly to small-scale microgrids [4,17].

Vitkova and Vitasek [18] show that the integration of technologies such as heat pumps, PV installations, and gray water recovery significantly reduces costs and utility consumption. In their study, the economic benefits exceed the initial costs, confirming the feasibility of the Total Performance method strategy in practice. Advanced energy management systems (EMS) enable real-time optimization of energy flows and cost savings. Parallel to this, the industry is seeing the rise in low-carbon construction materials: carbon-cured concrete, recycled industrial bricks, and Carbon Capture, Utilization and Storage (CCUS) technologies. While these remain costly, they hold the potential to drastically reduce a project's carbon footprint. Liu et al. [19] emphasize the centrality of early LCA in reducing both embodied and operational carbon in residential construction, reinforcing the need to integrate LCA and energy modeling. Digitization of the design and construction process especially the use of BIM and digital twins supports better decision-making, quality control, and long-term building management. Real-time sensor data can not only automate building systems but also validate predicted energy performance and enhance life-cycle tracking [20–22].

Energy efficiency is also a social issue. Well-designed and retrofitted buildings improve quality of life, reduce energy bills, and protect vulnerable populations from energy poverty, which affects millions of households across Europe [23,24]. Proper occupant education is crucial to realizing expected energy outcomes. Without user engagement, technical systems are underutilized, decreasing a project's actual efficiency [25,26]. At the same time, green finance mechanisms are gaining traction: green mortgages, energy performance-based loans, energy service contracts (ESCOs), and renovation grants are all making energy-efficient housing more accessible and appealing to developers and consumers alike [27,28].

Nguyen et al. [20] demonstrate that simulation-based optimization allows designers to evaluate various heating, ventilation, and air conditioning (HVAC) and envelope configurations, perfectly aligning with Total Performance objectives. Hidalgo-Fort et al. [29] show that affordable Internet of Things (IoT)-based SHM systems can bridge the performance gap by offering real-time feedback. Meanwhile, Vijayan et al. [4] describe CCUS-enhanced concrete solutions capable of sequestering up to 20% of carbon emissions, giving developers powerful new tools to reduce lifecycle emissions. Ajaz and Bernell [30] present residential microgrids as a viable pathway for self-sufficient and low-carbon neighborhoods, demonstrating how legislative and institutional support in California facilitated seamless integration of decentralized systems alongside the central grid.

Residential construction is entering a new era shaped by digital tools, data, and environmental accountability. Developers who commit to Total Performance strategies will not only meet tightening legal standards but also gain market differentiation and the trust of environmentally aware buyers. The future of housing lies not merely in isolated efficient buildings but in creating integrated living environments, low-carbon, resilient, energy-optimized, and user-centric [31]. Total Performance provides a practical and scalable pathway to deliver on these ambitions in line with global climate and development goals.

This study aims to analyze the effectiveness of the Total Performance approach in improving the energy efficiency and environmental sustainability of modern residential buildings. The research uses a case study of a semi-detached house built in Poland to evaluate integrated energy systems, including heat pumps, mechanical ventilation with heat recovery, and automatic temperature control, through simulation and real-time monitoring of energy consumption. The study will verify compliance with Polish TS, assess economic viability, and explore the building's readiness for future integration with renewable energy sources, such as PV. Ultimately, the study aims to demonstrate that the Total Performance strategy provides a scalable, practical model for sustainable, low-carbon residential construction that aligns with the EU's decarbonization goals and the European Green Deal.

2. Materials

The subject of the study is a residential unit located within a two-unit semi-detached residential building. The unit presented on Figure 2 is situated in a building designed in the form of a modern barn. The driveway and one of the entrances to the building are located on the southern side, while the garden and terrace doors are situated on the northern side. One of the gable walls of the unit is an external wall facing west. The building is located in Grójec, Poland, on land that was previously used for agricultural and now is designated in the local spatial development plan as an area intended for single-family or semi-detached housing.

Figure 2. Object under review.

The ground floor of the residential unit consists of two functional zones. The first is the living area, accessible from the exterior through a vestibule, and comprises an office space and a dining room. The second, technical zone includes service areas such as the kitchen, utility room, corridors, and a restroom. The upper floor is accessible via a staircase leading from the vestibule located on the northern side of the building, as well as from the kitchen. This level constitutes a typical private zone and includes two bedrooms, two bathrooms, and living spaces, specifically two TV rooms. The entrance platforms are sheltered by the overhanging upper floor. The usable floor area of the unit is 122.12 m^2, while the volume of the temperature-controlled spaces amounts to 362.51 m^3.

Rainwater from the roof and hardened surfaces is discharged onto biologically active land, which contributes to reducing the consumption of water from the municipal water supply. Additionally, water used by occupants for activities related to the maintenance of the building or surrounding area is measured by a separate sub-meter, allowing for a reduction in wastewater discharge fees.

The central heating system of the building is equipped with devices that enable automatic regulation of indoor temperatures in individual usable rooms, taking into account the specific preferences of the occupants with respect to days of the week and times of day. The system controlling the central heating installation will be connected to an external weather sensor, allowing the heating medium's parameters to be adjusted according to current atmospheric conditions. These solutions enable energy savings of up to 30% annually, as confirmed by studies on weather-based heating control in residential buildings [32].

The residential unit is equipped with an air-to-water heat pump—Panasonic Aquarea High Performance KIT-WC09J3E5-1 (bi-bloc, 9 kW) (Panasonic AVC Networks Czech s.r.o., Pilsen, Czech Republic) (Figure 3). The heat pump serves as the primary source of space heating and DHW for the occupants. According to the manufacturer, under moderate climate conditions, the unit achieves a coefficient of performance (COP) of 4.90 and a seasonal coefficient of performance (SCOP) of 3.32. The device holds an A+++ energy efficiency rating (for W35 °C). In addition to its core functions of heating and DHW production, the heat pump also provides cooling and automatic defrosting capabilities.

Figure 3. Air-to-water heat pump.

Additionally, in order to reduce electricity consumption associated with the operation of the heat pump, the system includes a DHW tank and a thermal buffer. The entire heating system within the residential unit has been implemented using underfloor heating technology, shown in Figure 4. This allows for a reduction in heating costs by maintaining lower temperatures in the heating circuit compared to traditional radiators.

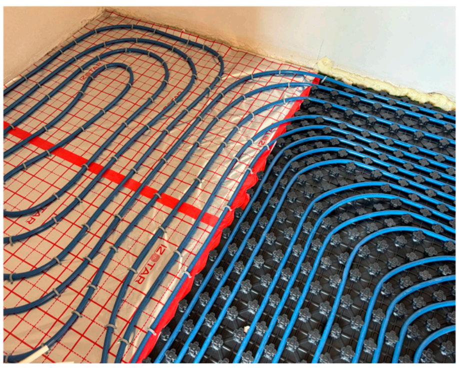

Figure 4. Underfloor heating system.

Furthermore, a pre-installed air conditioning system has been prepared for future integration of indoor units. One internal connection point has been installed on each floor—ground and upper—strategically located to allow for the heating or cooling of the largest possible usable area within the unit. This approach also minimizes the directly conditioned space and reduces costs associated with the purchase of indoor air conditioning units.

The residential unit is also equipped with a heat recovery ventilation (HRV) system, a type of mechanical supply and exhaust ventilation with heat recovery functionality. The ventilation shaft, which collects the entire air volume from the unit, is connected to a Komfovent heat recovery unit (Figure 5). The heat recovery system contributes to thermal regulation within the unit during both winter and summer, thereby enhancing occupant comfort year-round. An additional benefit of the system is the filtration of incoming outdoor air through filters installed within the HRV unit, which improves indoor air quality.

Figure 5. Komfovent heat recovery unit and HRV installations.

None of the residential units within the development is currently equipped with a PV installation. However, in each unit, technological conduits using protective tubing have been installed, leading to the non-habitable attic space and directly to the electrical distribution board. This solution allows for the future installation of PV panels at a time convenient for the occupants, without the need to interfere with finished or load-bearing elements of the unit.

The external walls of the unit are constructed from 18.8 cm thick ceramic blocks, which exhibit favorable thermal insulation properties. These walls have been insulated with graphite-enhanced polystyrene, which offers a more advantageous thermal conductivity coefficient λ of 0.033 W/(m·K), compared to conventional facade polystyrene, where λ values may reach as high as 0.045 W/(m·K). A summary of all envelope components included in the unit's energy performance assessment is presented in Table 1.

The residential units include a non-habitable attic which, after the application of thermal insulation, serves an important role as a thermal buffer. It functions as an insulating layer between the heated interior of the unit and the cold external air. In the case described, insulation was also applied to the ceiling below the attic, effectively reducing heat loss through the roof. During the summer months, this layer helps limit the amount of heat entering the living spaces, particularly under intense sunlight. By reducing temperature fluctuations, the attic space contributes positively to the durability of the roof structure and the performance of building materials. It is also worth noting that, despite being non-habitable, the attic may serve as a storage area.

The monitoring protocol covered the period from December 2024 to April 2025, encompassing a wide range of outdoor temperatures from −3 °C to +8 °C to ensure the representativeness of varying weather conditions. Data were recorded at an hourly interval using the integrated monitoring system of the air-to-water heat pump. During this period, the dwelling was fully occupied, and no constraints were imposed on occupant behavior, enabling the capture of authentic usage patterns and comfort settings. This approach allowed for assessing the influence of actual user interactions with the installed systems, providing valuable insights into potential discrepancies between design assumptions and operational performance.

Table 1. Building Envelope Components.

Component Name	Component Description	Thermal Transmittance U [W/(m^2·K)]	
		Achieved	Required
Interior door	Interior door	1.30	No requirement
Exterior door	Exterior door	1.30	1.30
External window and balcony door	External window and balcony door	0.81	0.90
Ground floor	Sand (0.3 m, λ = 2.000 W/(m·K)); Lean concrete (0 m, λ = 1.050 W/(m·K)); Thick foil (0.001 m, λ = 0.200 W/(m·K)); PE foil (0.001 m, λ = 0.200 W/(m·K)); Polystyrene (0.15 m, λ = 0.038 W/(m·K)); Concrete screed (0.05 m, λ = 0.120 W/(m·K)); Finish layer (0 m, λ = 0.200 W/(m·K))	0.21	0.30
Inter-storey floor	Finish layer (0.02 m, λ = 0.200 W/(m·K)); Leveling layer (0.05 m, λ = 0.120 W/(m·K)); Insulation layer (0.05 m, λ = 0.040 W/(m·K)); Vapor barrier foil (0.001 m, λ = 0.300 W/(m·K)); Reinforced concrete slab (0.18 m, λ = 1.700 W/(m·K)); Interior plaster (0.015 m, λ = 1.000 W/(m·K))	0.48	No requirement
Ceiling below unheated attic	Thermal insulation (0.25 m, λ = 0.038 W/(m·K)); Truss structure (0.18 m, λ = 2.500 W/(m·K)); Foil (0.001 m, λ = 0.200 W/(m·K)); Plasterboard (0.125 m, λ = 0.230 W/(m·K))	0.14	0.15
External wall	Thin-coat plaster (0.015 m, λ = 1.000 W/(m·K)); Polystyrene (0.2 m, λ = 0.033 W/(m·K)); Ceramic block (0.188 m, λ = 0.300 W/(m·K)); Interior plaster (0.015 m, λ = 1.000 W/(m·K))	0.15	0.20
Internal wall	Interior plaster (0.015 m, λ = 1.000 W/(m·K)); SILKA CLASS 15 (0.08 m, λ = 0.530 W/(m·K)); Interior plaster (0.015 m, λ = 1.000 W/(m·K))	2.27	No requirement
Internal wall	Interior plaster (0.015 m, λ = 1.000 W/(m·K)); Ceramic block (0.188 m, λ = 0.300 W/(m·K)); Granulated mineral wool 40 (0.02 m, λ = 0.040 W/(m·K)); Ceramic block (0.188 m, λ = 0.300 W/(m·K)); Interior plaster (0.015 m, λ = 1.000 W/(m·K))	0.49	No requirement

3. Methods

The energy analysis of the unit was based on two complementary data sources: the official EPC and real-time operational data obtained from the internal monitoring system of the air-to-water heat pump. The monitoring system recorded hourly electricity consumption during the heating season, spanning the months of December 2024 to April 2025. This period was selected due to its high and variable heating loads, which provide a reliable and representative benchmark for evaluating the building's energy performance under real-world operating conditions. Importantly, the building was already in use by occupants during this time, allowing for the inclusion of actual user behavior and thermal comfort settings in the analysis. The recorded data were aggregated and filtered to validate simulation results and to identify potential discrepancies between the theoretical energy demand and actual performance. This contribute to a more accurate and practice energy evaluation.

To ensure compliance with the Polish technical requirements set out in technical specifications (TS) [33], the simulation and assessment of the building's energy profile were carried out using ArCADia–TERMOCAD 8.0 software. This certified and regulation-compliant tool is widely recognized in Poland for generating EPCs and performing energy performance simulations across residential and public building types. The software supports the detailed digital modeling of a building's physical parameters, including its envelope components, internal partitions, and HVAC systems. It allows users to define thermal zones and evaluate the interaction between building systems and weather conditions. It calculates key indicators such as useful energy demand (UED), final energy demand (FED), and primary non-renewable energy demand (PED), for multiple end uses, including space heating, ventilation, DHW, cooling, and lighting. Furthermore, ArCADia–TERMOCAD 8.0 software enables the simulation of renewable energy systems, making it suitable for assessing both the current state of the building and future upgrade scenarios, such as the integration of PV panels.

This study used a predictive energy model of the building based on its actual, completed characteristics, rather than at the design stage. This means that the existing building was mapped along with its technical parameters and installation systems, and then an energy simulation was performed using ArCADia–TERMOCAD 8.0 software. This approach allows for a comparison of the calculation results with data obtained from monitoring actual energy consumption and enables an analysis of the energy efficiency gap.

The DHW system is based on an air-to-water heat pump powered by electricity from the national power grid. Thus, the entire DHW system is based on electricity as an energy carrier. This form of electrification of heating and DHW systems is in line with the climate policy of the European Union (EU) and Poland, supported, among other things, by subsidy programs for heat pumps and the development of prosumer energy (e.g., PV).

The combination of simulation-based modeling and empirical monitoring enables a more holistic and reliable assessment of the building's energy behavior, capturing both the theoretical performance potential and actual in-use characteristics of the installed technologies. This dual-source methodology also provides valuable insights into the so-called "performance gap"—the divergence between energy consumption predicted during the design phase and that observed during actual operation.

By directly comparing simulated and real data, the study supports evidence-based decision-making, highlights the effectiveness of the applied systems, and points to areas of potential optimization—particularly in the context of DHW usage and renewable energy readiness. Such an approach aligns with best practices in energy-efficient building evaluation and supports the continuous improvement of design standards and energy certification methods.

Table 2 presents a detailed breakdown of the heating system parameters, highlighting their contribution to overall energy efficiency and CO_2 emissions.

Based on the data presented in Table 2, it is possible to calculate the value of the annual demand for useful energy for heating and ventilation. In this case, the energy performance assessment was carried out in accordance with TS [33], using the calculation method. The software used therefore applies the following Formula (1):

$$Q_{H,nd} = \sum_{m=1}^{12} \left[(H_T + H_V) \cdot (T_{int} - T_{ext,m}) \cdot t_m - \eta \cdot Q_{g,m} \right] \quad (1)$$

where

$Q_{H,nd}$—annual useful energy demand for space heating [kWh/year],
H_T—heat loss coefficient due to transmission [W/K],
H_V—heat loss coefficient due to ventilation [W/K],
T_{int}—indoor temperature [°C],
$T_{ext,m}$—average outdoor temperature in month m [°C],

t_m—number of hours in month m [h],
η—utilization factor of heat gains [−],
$Q_{g,m}$—heat gains in month m (e.g., from occupants, appliances, solar radiation) [kWh].

Table 2. Summary of heating system parameters in the context of energy efficiency and CO_2 emissions.

Heat Source Name	Air-To-Water Heat Pump			Unit
Percentage share of the source in the group			100	%
Annual demand for useful energy for heating		$Q_{H,nd}$	959.82	kWh/year
Generation		**Efficiency of generation**		
Type of fuel	National power grid—Electric energy	w_H	2.5	-
Type of heat source	Air/water heat pump, compressor, electrically driven	W_{e,H,CO_2} $\eta_{H,g}$	93.87 3.00	t CO_2/TJ -
Control		**Efficiency of control**		
Type of installation	Water underfloor heating in case of central and local control with two-position or proportional P controller	$\eta_{H,e}$ $\eta'_{H,e}$ X	0.89 0.89 1.00	-
Distribution		**Efficiency of distribution**		
Type of heating installation	Central heating from local heat source located in the heated building with insulated pipes, fittings and devices installed in heated space	$\eta_{H,d}$	0.96	-
Heat accumulation		**Efficiency of accumulation**		
Tank parameters	Heat storage tank in the heating system located in the heated space	$\eta_{H,s}$	0.95	-
Auxiliary devices				
Annual demand for final electric energy for the operation of auxiliary heating and ventilation system devices		$E_{el,pom,H,v}$	392.01	kWh/year
		w_{el}	2.5	-
		w_{e,pom,H,CO_2}	93.87	-
Type of fuel	National power grid—Electric energy	$\eta_{H,tot}$	2.44	-

Similar data are required in order to obtain information on the energy demand for DHW preparation. This is performed using Formula (2):

$$Q_{W,nd} = V_{w,rok} \cdot \rho_w \cdot c_w \cdot (T_{hot} - T_{cold}) \quad (2)$$

where

$Q_{W,nd}$—annual useful energy demand for DHW preparation [kWh/year],
$V_{w,rok}$—annual volume of hot water consumption [m^3/year],
ρ_w—density of water [kg/m^3],
c_w—specific heat capacity of water [kWh/(kg·K)],
T_{hot}—temperature of hot water [°C or K],
T_{cold}—temperature of cold water [°C or K].

It is evident that both Formulas (1) and (2) have their origins in Polish technical conditions. However, it is important to note that both are derived from ISO 52016-1 [34], which concerns the methodology for calculating energy demand for heating and cooling buildings and preparing DHW. The summary of data related to DHW production is presented in Table 3.

Table 3. Summary of DHW system parameters in the context of energy efficiency and CO_2 emissions.

Heat Source Name		**Air-to-Water Heat Pump**		**Unit**
Percentage share of the source in group:			100	%
Annual demand for useful energy for DHW		$Q_{w,nd}$	2980.32	kWh/year
Generation		**Generation efficiency**		
Type of fuel	National power grid—Electric energy	w_H	2.5	-
		W_{e,H,CO_2}	93.87	t CO_2/TJ
Type of heat source	Air/water heat pump, compressor, electrically driven	$\eta_{w,g}$	2.60	-
Distribution		**Distribution efficiency**		
Type of DHW installation:	Central hot water systems—systems with circulation loops and working time limitation, with installation risers and insulated pipes	$\eta_{W,d}$	0.80	-
	Number of hot water draw-off points up to 30			
Heat accumulation		**Accumulation efficiency**		
Storage tank parameters	DHW storage tank manufactured after 2005	$\eta_{W,s}$	0.85	-
Auxiliary devices				
Annual demand for final electric energy for operation of DHW preparation system auxiliary devices		$E_{el,pom,H,v}$	193.20	kWh/year
		w_{el}	2.5	-
		w_{e,pom,H,CO_2}	93.87	-
Type of fuel	National power grid—Electric energy	$\eta_{H,tot}$	2.44	-

4. Results and Analysis

The most important indicator in terms of the current Polish regulatory framework is Primary Energy (PE). This value reflects the environmental impact of the building's energy consumption by including the input of non-renewable PE sources (e.g., coal burned in power plants) and the conversion factors applied to electricity. Table 4 presents five key indicators related to the energy consumed by the building.

The annual UED indicator refers to the amount of energy required to provide space heating/cooling and DHW, without accounting for system losses or the efficiency of energy sources. It represents the sum of all UED components per square meter of building area.

Final energy is the actual energy drawn from the grid, factoring in the efficiency of devices, distribution losses, and other system characteristics.

In the analyzed residential building, energy consumption during the winter season confirmed the high efficiency of the installation solutions used. Figure 6 shows the actual electricity consumption of the heat pump during the first year of operation of the building, broken down by month. During the period under study, the main task of the device was to provide energy for space heating. It should be noted that in the months preceding the actual use of the building, it was heated in order to stabilize the thermal conditions and protect the finishing elements from the adverse effects of low temperatures.

Table 4. The Annual Demand Indicators for Useful, Final, and Primary Energy.

Type of Carrier or Energy	Heating and Ventilation	Domestic Hot Water	Cooling	Built-In Lighting	Total	Unit
Annual useful energy demand indicator						
Electric energy	7.86	24.09	0.00		31.95	kWh/(m^2·year)
Share	24.60	75.40	0.00		100.00	%
Annual final energy demand indicator						
Electric energy	6.44	15.19	0.00	0.00	21.63	kWh/(m^2·year)
Total	6.44	15.19	0.00	0.00	21.63	kWh/(m^2·year)
Share [%]	29.77	70.23	0.00	0.00	100.00	
Annual non-renewable primary energy demand indicator						
Electric energy	16.09	37.96	0.00	0.00	54.05	kWh/(m^2·year)
Total	16.09	37.96	0.00	0.00	54.05	kWh/(m^2·year)
Share	29.77	70.23	0.00	0.00	100.00	%

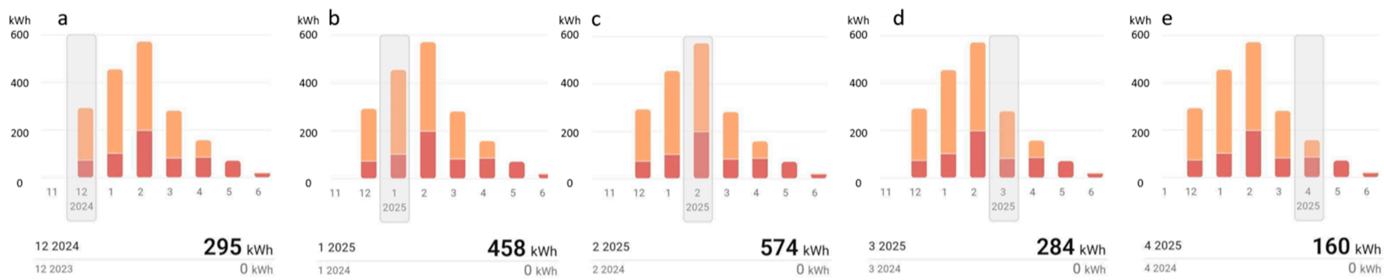

Figure 6. Monthly breakdown of energy use during the monitored season (orange—heating, red—hot water): (**a**) December 2024, (**b**) January 2025, (**c**) February 2025, (**d**) March 2025, (**e**) April 2025.

As shown in Figure 7, variable average outdoor temperatures were observed, which significantly affected the level of energy demand. The highest consumption occurred in the months with the lowest temperatures.

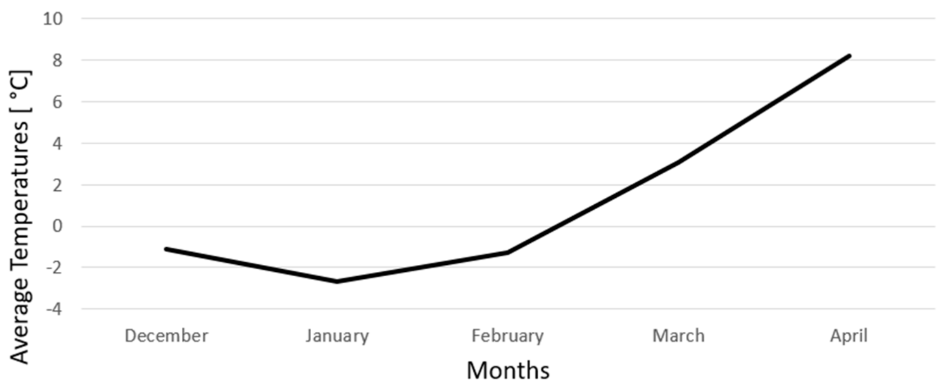

Figure 7. Average monthly temperature in Grójec.

Throughout the entire period, the indoor temperatures remained stable and in line with the assumptions: approximately 24 °C in bathrooms and toilets and 20 °C in other usable spaces. The energy indicators obtained confirm the high efficiency of the building—the annual non-renewable PE demand indicator was 54.05 kWh/(m^2·year), which means a significant safety margin in relation to the applicable TS standards [33] equals 70 kWh/(m^2·year) for this type of buildings, as shown on Figure 8.

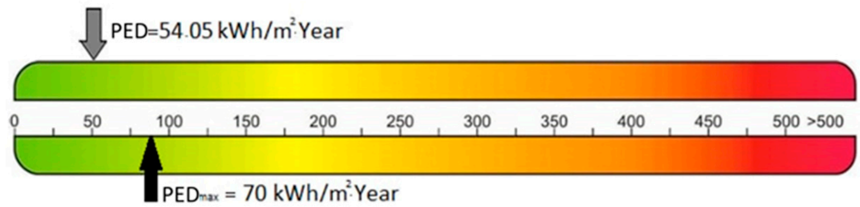

Figure 8. The annual non-renewable PE demand indicator PED.

This efficiency was achieved through a combination of modern technologies: heat pumps, underfloor heating, mechanical ventilation with heat recovery, and an automatic control system. At the same time, the analysis showed that the largest share of total energy consumption was accounted for by the preparation of DHW, which may be a starting point for further optimization measures, particular through the use of the planned infrastructure for a PV installation.

In the context of residential heating in Poland, three technologies remain the most commonly used due to their availability, maturity, and cost-efficiency: air-to-water heat pumps, natural gas boilers, and biomass boilers using wood pellets. Each of these systems operates with a different energy carrier and level of efficiency, which directly affects their overall performance and operating costs. To assess and compare their economic viability, the analysis was based on the building's calculated non-renewable PE demand, which amounts to 54.05 kWh/m^2/year according to the EPCs. For a usable floor area of 122.12 m^2, this yields an annual PE consumption of 6599.14 kWh/year. To estimate the real-world operating costs of the heating systems, this value must be converted into FED, using the PE conversion factor for electricity. This adjusted value serves as a basis for cost comparison between different systems. The following assumptions based on the Polish market were made:

- Air-to-water heat pump: SCOP = 3.0, electricity price = PLN 0.87/kWh
- Natural gas boiler: efficiency = 98%, net calorific value of the fuel = 7 kWh/m^3, gas price = PLN 2.56/liter
- Pellet boiler: efficiency = 80%, net calorific value of the fuel = 5 kWh/kg, pellet price = PLN 1.35/kg.

In combustion-based systems, such as gas or pellet boilers, the efficiency represents the fraction of input energy effectively converted into heat. A 98% efficient gas boiler requires approximately 1.02 kWh of gas to produce 1 kWh of heat, while an 80% efficient pellet boiler requires about 1.25 kWh of pellets. In contrast, a heat pump with SCOP 3.0 can deliver 3 kWh of thermal energy using only 1 kWh of electricity, by transferring ambient heat from the surrounding environment. The resulting energy input and annual operating costs are:

- Heat pump:
  Input energy = 6599.14 kWh/year
  Cost of 1 kWh of heat = 0.87/3 = PLN 0.29
  Annual cost = 6599.14 × 0.29 = PLN 1913.75
- Gas boiler:
  Input energy = 6599.14 kWh/year
  Cost of 1 kWh of heat = 2.56/7/0.98 = PLN 0.373
  Annual cost = 6599.14 × 0.373 = PLN 2461.48
- Pellet boiler:
  Input energy = 6599.14 kWh/year
  Cost of 1 kWh of heat = 1.35/5/0.85 = PLN 0.338
  Annual cost = 6599.14 × 0.338 = PLN 2230.51

Despite variations in energy prices, the high operational efficiency of the heat pump results in the lowest annual energy cost among the analyzed systems. Gas boilers remain a viable alternative, particularly where gas infrastructure is already in place, while pellet boilers, although offering low fuel costs, require more manual operation and maintenance.

Although the initial cost of investing in an air-to-water heat pump system is usually higher than that of conventional heating systems, such as gas or pellet boilers, the long-term economic and environmental benefits often justify the expense. Thanks to its high SCOP, a heat pump significantly reduces annual energy consumption, which can translate into lower operating costs over time.

Importantly, heat pumps are currently among the most promoted technologies in national and EU energy transition strategies. In Poland, they are eligible for financial support under programs offering partial reimbursement of installation costs. These subsidies can significantly reduce the initial investment costs, thereby shortening the payback period and improving the cost-effectiveness of this solution compared to fossil fuel-based alternatives.

In this context, the integration of heat pump systems—especially in combination with renewable electricity generation (e.g., PV panels) and smart energy management is a forward-looking approach that supports both climate goals and household budget optimization. When using available support mechanisms, the return on investment can be significantly more favorable than with traditional heating systems. A preliminary simulation was carried out assuming a 4 kWp PV installation, i.e., approximately 4000 kWh of energy produced annually. This would cover almost 61% of the building's annual electricity consumption, reducing PE demand to 21.08 kWh/(m^2·year) and potentially saving PLN 1167.39 per year.

It is also important to emphasize that, contrary to the assumptions of the EPC, actual monitoring data indicate that space heating was the dominant contributor to electricity consumption during the analyzed period. Based on the previously established assumptions and the data presented in Figure 6, the total electricity consumption of the heat pump from December to April amounted to 1771 kWh, which corresponds to a cost of PLN 513.59 for that period. This value represents approximately 27% of the annual non-renewable PED, which is a highly plausible result considering the significant decrease in heating demand outside of the winter months.

In May, energy consumption was primarily related to DHW preparation, and did not exceed 70 kWh. Until mid-June, electricity consumption remained low and reached only about 18 kWh, further confirming the seasonal nature of space heating as the PE load in this building.

Differences between the EPC values and the actual readings from the heat pump may result from how the building is actually used and the assumptions made during the design phase. In ArCADia–TERMOCAD 8.0 software, a specific number of water draw-off points is assumed, which does not necessarily mean that all of them will be used in practice. The high share of DHW in total energy use may be linked to user habits or conservative assumptions in the design stage regarding water usage. Implementing solar thermal collectors or optimizing circulation loops could significantly reduce DHW energy demand. Future studies should investigate seasonal DHW profiles and evaluate alternative solutions for load reduction.

During the energy consumption measurements, the air conditioning system had not yet been installed, although, as mentioned earlier, the full infrastructure for the future connection of indoor and outdoor units had been prepared. Therefore, the user's influence on energy consumption during the analyzed period was limited, as it was not possible to interfere with the operation of the cooling systems or to adjust them individually.

5. Discussion

When compared to European benchmarks, the analyzed building performs favorably relative to the NZEB requirements, which typically set PED thresholds below 60 kWh/(m^2·year) for similar climate zones [35]. However, the building's annual heating demand remains higher than the stringent Passive House standard of approximately 15 kWh/(m^2·year) for space heating [36]. This suggests that while the Total Performance approach achieves compliance and significant efficiency improvements, further optimization could be explored to approach Passive House-level performance, particularly regarding envelope insulation and passive design measures.

The choice of heat source has a key impact on the profitability of the investment. Scientific articles show that for many households air-to-air pumps are cost-effective [37–39]. Numerous scientific studies confirm that air-to-air heat pumps offer high seasonal performance and economic viability, particularly in regions with moderate climate conditions [36,40–42]. However, there are also studies indicating that the efficiency of the equipment varies, for example, Brudermueller et al. [43] shows that 17% of air pumps do not meet SCOP standards, indicating the need for quality testing after installation. Deng et al. [44] indicate, in their study, that the actual COP of air source heat pumps in some devices was only 2.59, while the design values were much higher, reaching as high as 4.1. This means that in practice heat pumps operate up to 20–30% less efficiently than assumed. The authors point to equipment oversizing, low-load operation and problems with heat exchangers and system control as the main reasons. Nolting et al. [45] point out that the actual efficiency of heat pumps often deviates significantly from the values declared on energy labels. Their analysis showed that differences can range from −24% to as much as +80% relative to catalog data, especially for air source heat pumps. Key reasons for these discrepancies include local climatic conditions, oversizing of equipment, improper selection of the bivalent point and control strategies used. The authors emphasize that energy labels, to be truly helpful to consumers, should take into account variable operating conditions and local conditions, which have a significant impact on actual system performance. These are another problems indicating that it is not just a lack of user awareness that is the result of the performance gap. The role of the user remains crucial despite technological advances lack of informed use can lead to discrepancies in monitored efficiency. Systematic reviews confirm that residents knowledge and behavior significantly shape the efficiency achieved [11,12].

In Poland, gas and pellet boilers are still relatively common in residential buildings, especially in older developments and suburban or rural areas. As indicated by national energy statistics, a significant proportion of single-family residences continue to depend on these systems due to their historical prevalence and the accessibility of fuel. Nevertheless, the electrification of heating systems is a key component of both EU and national policies. The Clean Air Program (Polish: "Program Czyste Powietrze") is a government initiative that aims to reduce air pollution by promoting the replacement of traditional heat sources, such as coal and gas, with modern, low-emission alternatives. These include heat pumps, which are considered to be more environmentally friendly. Financial subsidies and tax relief schemes are available for households undertaking such upgrades. Furthermore, Poland's updated EPC methodology, which is now aligned with EU directives, incorporates higher ratings and additional star categories for buildings that use renewable energy systems. The evaluation of residential buildings equipped with heat pumps or electric heating supported by PV systems is more favorable, reflecting their reduced carbon footprint and higher energy efficiency standards [34,46]. The overarching objective of this certification system is to incentivize the transition away from fossil fuel-based systems, including gas and pellet boilers, and to reward buildings that contribute to decarbonization goals.

In this context, the Total Performance philosophy offers a comprehensive framework integrating the technical, environmental, and social aspects of building energy use [47–49]. This framework addresses both the design and operational phases. Unlike traditional approaches, which focus primarily on prescriptive technical standards, Total Performance emphasizes aligning energy efficiency, occupant comfort, building durability, and future adaptability from a LCA perspective [50,51]. Achieving sustainable building performance requires a continuous feedback loop between design intent, actual operation, and user engagement [52–54]. Consequently, it advocates incorporating digital tools, such as BIM, real-time monitoring, and user education, to bridge the performance gap and optimize outcomes throughout the building's lifecycle [55,56].

It is worth noting that similar optimization approaches have been successfully applied in non-residential contexts, such as rural schools, to enhance energy efficiency through passive design strategies. For instance, Es-sakali et al. [57] applied multi-objective optimization using EnergyPlus software and genetic algorithms to evaluate the impact of bio-based insulations, shading devices, and roof vegetation on energy performance and indoor comfort. While their study focused on educational buildings in Morocco, the methodological parallels underline the importance of integrating advanced optimization tools and climate-responsive design measures in bridging the gap between simulated predictions and real-world performance also in residential buildings.

Preparing buildings for other installations (e.g., PV) as an integral part of the construction project allows for subsequent retrofitting without costly adaptation works, which increases the flexibility of investments and fits in with climate goals. Equally important is foresight in planning future energy upgrades. Considering systems such as PV panels at the design stage—for example, through pre-installed cable routes, acceptable roof loading and inverter-adapted switchgear—minimizes technical and financial barriers to future upgrades. Studies show that "solar-ready" homes are much cheaper to adapt to PV installations than those that are adapted post-factum. The case of retrofitting ventilated facades with a PV module, shown in the study to be easy to replicate, also confirms that planning at the construction stage avoids costly adaptations [58].

This is an aspect that makes it possible to reduce, and in many cases completely eliminate, the problem of power outages or disruptions. Although such situations are becoming increasingly rare, the problem still remains, especially since much of Poland's grid infrastructure is outdated, with insufficient work to modernize it. As Kryszk et al. [59] point out, as much as 39% of overhead lines and 33% of substations in Poland are over 40 years old. It is, therefore, important to keep in mind the consequences of the increasing electrification of energy sources in buildings, which is also associated with certain limitations. A particularly relevant example is the increasing incidents of power outages observed in Western European countries.

Adopting a flexible, anticipatory strategy aligns with evolving climate policy objectives, such as the European Green Deal and decarbonization mandates, and enhances the resilience and long-term value of real estate assets [60,61]. Buildings designed to accommodate emerging renewable energy technologies are better positioned to absorb market fluctuations in energy prices and comply with tightening regulatory frameworks [62,63]. This strategic adaptability aligns with the core principles of Total Performance, which emphasizes future-proofing investments through integrated, multidimensional optimization. Considering operational data, user behavior, and technological advancements concurrently advances the Total Performance philosophy, providing a practical, scalable pathway toward sustainable residential construction that is economically viable, environmentally responsible, and socially inclusive [64–66].

Integrating Total Performance principles into the selection and deployment of heating systems, as well as the strategic preparation for renewable energy retrofits, establishes a solid foundation for closing the performance gap. This approach ensures that buildings meet regulatory requirements at completion and continue to perform efficiently through-out their service life. Buildings can adapt dynamically to changing environmental conditions, user needs, and technological innovations.

Research on air-to-water heat pumps in Poland needs to be further developed to obtain a complete picture of their performance under domestic conditions, especially in the context of assessing building Total Performance. It is crucial to conduct analyses that cover the entire lifetime of these devices, thus eliminating the problem of limiting observations to the heating season only, and taking into account the variability of climatic conditions throughout the year, as well as the varying profiles of building use. This type of approach is essential, especially for real estate development projects, where technology decisions have a significant impact on both operating costs and the market value of the property, as well as meeting stringent energy standards. Equally important would be a study of public awareness of the use of not only renewable energy sources, but also modern technologies, including heat pump-based heating systems. Such an analysis could provide information on the mental and social barriers to implementing innovative solutions and the level of acceptance of low-carbon technologies among users and investors. This is particularly important in the context of the growing requirements for energy efficiency and sustainable development, which apply to both new construction and modernization projects, and in light of the still strong attachment of part of the Central and Eastern Europe population to fossil fuels as the primary source of energy.

6. Conclusions

An analysis of the actual energy consumption of the modern residential building revealed the effectiveness of the technological solutions used and confirmed that the Total Performance approach design strategy is effective both in theory and in practice. The building achieved a non-renewable PED index of 54.05 kWh/(m^2·year), which is a clear safety margin against the 70 kWh/(m^2·year) limit in force in Poland. This demonstrates not only compliance with legal requirements, but the investment's preparedness for upcoming changes in the EU's energy and climate policy. Several key technologies worked together to achieve energy efficiency: an air-to-water heat pump, underfloor heating, mechanical ventilation with HRV and an automatic temperature control system. These systems ensured not only year-round thermal comfort, but also a significant reduction in electricity consumption. Monitoring of energy consumption during the heating season revealed that the largest load was the space heating system, rather than hot water preparation, was the largest load, contrary to the energy certificate's assumption. Therefore, design analyses, while useful, should be supplemented with actual measurements to minimize the efficiency gap.

In terms of economics, it was shown that among the compared heat sources (heat pump, gas boiler and pellet boiler), the heat pump offers the lowest annual operating costs, despite the higher initial investment. Assuming a seasonal efficiency of SCOP = 3.0 and electricity costs of PLN 0.87/kWh, the total cost of heating the building was only PLN 1913.75 per year, which was lower than that of both a gas and a pellet boiler. Therefore, investment in heat pump technology is becoming increasingly cost-effective, especially when combined with appropriate subsidy programs.

Another important element of the Total Performance strategy was the building's readiness to integrate renewable energy sources, particularly a PV system. Although the PV system has not yet been installed, the existing infrastructure allows for its future implementation without disruption. Thus, the building has the potential to meet all of its energy needs with renewable energy, which would significantly reduce its carbon footprint and increase its residents' energy independence.

While this case study demonstrates the technical and economic viability of the Total Performance approach in semi-detached residential properties, its scalability and affordability for larger-scale residential projects, such as social housing developments, require further investigation. Factors such as higher initial capital costs, supply chain capacity, and the socioeconomic profile of occupants could significantly influence feasibility. Future research should include comprehensive cost–benefit analyses and policy considerations to assess how Total Performance strategies can be effectively deployed at scale.

The conclusions of the study are as follows:

- The building significantly exceeds the energy requirements of Poland, making it compatible with the long-term goals of the EU's decarbonization policy.
- The high efficiency of the applied heating and ventilation systems was confirmed in real conditions, which is a strong argument for their wider use in development construction.
- Hot water preparation accounted for the largest share of energy consumption, suggesting the possibility of further optimization—for example, by installing PV systems and using intelligent EMS.
- A heat pump proved to be the most cost-effective heating solution, which is particularly important in the context of rising gas prices and policies to move away from fossil fuels.
- Preparing a building for integration with renewable energy sources provides investment flexibility and allows owners to gradually increase energy efficiency in the future.

Strategically, the case presented shows that the Total Performance approach—integrating energy efficiency, occupant comfort, preparation for future retrofits, and actual operating data can become the new standard in residential construction. The model is not only scalable and compliant with current regulations, but also ready for changing climatic, social and technological conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ANN	Artificial Neural Network
BIM	Building Information Modeling
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon Dioxide
COP	Coefficient of Performance [-]
DHW	Domestic Hot Water [-]
EMS	Energy Management Systems
EPC	Energy Performance Certificate
ESCO	Energy Service Contracts
EU	European Union
EV	Electric Vehicle
FED	Final Energy Demand [kWh/(m^2·year)]
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation and Air Conditioning
IoT	Internet of Things
LC	Life Cycle
LCA	Life Cycle Assessment
PE	Primary Energy [kWh/(m^2·year)]
PED	Primary Energy Demand [kWh/(m^2·year)]
PV	Photovoltaic
SCOP	Seasonal Coefficient of Performance
SDGs	Sustainable Development Goals
SHM	Structural Health Monitoring
TS	Technical Specification
UED	Useful Energy Demand [kWh/(m^2·year)]

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