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Analysis of Internal Conditions and Energy Consumption during Winter in an Apartment Located in a Tenement Building in Poland

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Abstract: The residential sector of existing buildings has great potential in energy savings and the improvement of indoor conditions. The modernization of buildings is of particular concern to the policies of the European Union, local governments, and building users. The aim of this paper is to present an analysis of indoor parameters and energy consumption for heating for an apartment located in a pre-war tenement building before and after thermomodernization. The analysis was conducted for winter conditions and was based on measurements and simulations. Originally, the building had not undergone any thermomodernization actions since its reconstruction after WWII. Interior, exterior, and surface temperatures were recorded to describe the thermal conditions of the apartment, while gas meter readings were used to estimate energy consumption for heating purposes. WUFI Plus software (v.3.2.0.1) was used to estimate energy consumption and perform energy simulations for the apartment over an extended period of time. The best thermomodernization effect resulted from the replacement of windows and the inefficient heating system, avoiding surface condensation and reducing final energy consumption by more than 50%. The extended options resulted in energy savings higher than 70%. The presented analysis shows the importance of retrofit measures and proves that even a small improvement can bring significant benefits.

Keywords: residential building; indoor conditions; energy usage; energy simulations; heating season

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Citation: Laska, M.; Reclik, K. Analysis of Internal Conditions and Energy Consumption during Winter in an Apartment Located in a Tenement Building in Poland. *Sustainability* **2024**, *16*, 3958. https://doi.org/10.3390/su16103958

Academic Editor: Francesco Nocera

Received: 1 April 2024
Revised: 25 April 2024
Accepted: 28 April 2024
Published: 9 May 2024

1. Introduction

Existing buildings have great potential in energy conservation. The European Commission estimates that buildings are responsible for approximately 40% of EU energy consumption, where the building HVAC and DHW installations themselves consume about 80% of the energy consumed by citizens. This causes about 36% of the energy-related greenhouse gas emissions [1]. In terms of this information, one needs to focus on the residential sector that has a great potential in energy conservation. Because it reduces energy demand, improving the energy efficiency in buildings is considered, along with fossil fuels and renewable energy, to be the "sixth fuel" [2]. This term refers to the energy that can be saved, resulting in benefits such as reduced energy consumption and heating and cooling costs, and has a positive impact on occupant well-being and minimizes the environmental footprint regarding CO_2 production.

The aforementioned data are very important when main European cities are taken into consideration. Strict regulations [3] define thermal and energy indices, and thus force the use of renewable energy sources (RES). The application of RES-based solutions in newly constructed buildings that meet the criteria of thermal protection is relatively easy, whereas for existing buildings, lowering their energy consumption is challenging and costly, especially for old tenement houses. The European Commission estimates that "about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient" [1]. Publications [4,5] indicate that there is a correlation, but a non-linear one, between the energy consumption in residential buildings and the construction age. Aksoezen et al. [4] indicated that buildings constructed between 1947 and 1979 are characterized by the highest gas consumption of the analyzed building stock, while those built between 1921 and 1946 consume slightly less. Xu et al. [5] concluded that residential buildings built in the 1980s and 1990s consume more energy for space heating and cooling and that the energy consumption depends on the unit area and is lower in small-sized premises in high-rise buildings, while Gassar et al. [6] confirmed that the average number of rooms per apartment greatly influenced residential gas consumption. Also, other studies [7–9] indicate that there is a huge potential in energy conservation in existing buildings. Therefore, in this area, thermomodernization measures deserve special attention. The most common are related to interference with the building envelope. Parameters that affect the envelope energy efficiency can be categorized into façade design parameters, such as WWR (window–wall ratio), glazing type and shading, building material properties and construction, i.e., insulation, thickness and airtightness, and site parameters [10–17]. Yousefi et al. [11] added to that list occupant behavior. Furthermore, Hong et al. [18] also highlighted building services and energy systems, building operation and maintenance, and indoor environmental quality in order to minimize the issue concerning the energy performance gap between predicted and real energy consumption. Kim et al. [19] determined that solar gains and infiltration have a significant impact on energy consumption in residential apartment buildings. Hou at al. [20] analyzed how the variation in window thermal parameters affects the traditional dwelling's energy demand. Al-Shargabi et al. [21] stressed the importance of characteristics such as WWR and wall U-value as key factors that affect energy consumption, as low insulation performance is typical for glass used in windows compared to other construction materials [22]. Nadeem et al. [23] drew attention to the correlation between WWR and wall insulation with the conclusion that the rise in WWR value leads to a decrease in annual energy use in uninsulated constructions.

To ensure energy-efficient housing, the old glazing should be replaced with modern, triple-glazed windows that have a low heat-transfer coefficient and high airtightness [24–26]. Improving the thermal performance of external walls can be realized by adding an extra external layer of the insulating materials (polystyrene, mineral wool, etc.); applying IWI, internal wall insulation (using materials with low diffusion resistance like mineral wool or high-performance insulating panels, e.g., phenolic or resol insulation boards); or filling the air cavity with a low λ coefficient (polyurethane foam or various types of granulates made of glass wool, cellulose, or perlite) [14,27–30]. Further insulation measures may include insulating the internal walls, slabs, or roofs. The use of other innovative materials such as vacuum panels or phase-change materials is also possible [30,31]; however, due to the economic aspect, they are not yet widely used. Building thermomodernization also includes activities related to increasing the efficiency of the ventilation and the heat source. Most existing residential buildings are served by natural ventilation. During the thermomodernization, if possible, it is desirable to install a mechanical ventilation system with heat recovery; however, due to the technical feasibility, it is difficult to implement in individual apartments in tenement buildings. The exchange of a heat source for a more efficient one with the modernization of existing heating systems is more common and easier to implement but requires a deeper analysis including technical, legal, social, and economic aspects. Buildings located in the dense urban tissue may have access to the district heating system or gas network; those located in suburbs may have more opportunities to install sources based on renewable energy (heat pumps, PV panels, or solar collectors). It needs to be stressed that replacement with such a source is economically justified only when the building's energy demand is reduced in advance.

The thermomodernization of existing buildings, even those located in city centers, is possible and desired; however, in Europe, only 1% of them is renovated every year [32].

The thermal modernization actions are limited due to the number of reasons. The most important, especially addressing tenement buildings, are:

- Location: Such buildings are often located in a dense building tissue in city centers and areas protected by the conserver office. Some of the buildings, due to their architectural features, are the part of the historical heritage; therefore, each renovated action needs to be approved by the appropriate national heritage office;
- Technical limitations: Such buildings are the part of urban context; therefore, the local technical guidelines, subdivision and land ownership, and internal architectural and technical layout (e.g., access to ventilation shaft) determine the possible thermomodernization solutions;
- Division of ownership of the apartments: This is the crucial aspect when the building as a whole need to be modernized. This does not apply to individual flats, where the owner may exchange the windows or individual heating and DHW installations. However, all the actions need to follow other regulations if necessary;
- Level of wealth of tenement dwellers: Modernization measures often exceed the financial capabilities of individual families.

The aforementioned limitations are described further in [17,33].

In order to stimulate the thermomodernization process, the European Commission established EPBD [34] and a set of other documents [32,34–37], which emphasize the need for more effective renovations of the existing building stock. The documents oblige the European countries to apply the dedicated measures and subsidies to accelerate the renovation process toward carbon neutrality in 2050 and to fulfil the Sustainable Development Goals (SDG) [34–36,38]. This approach has a simultaneous positive effect, namely, it leads to an upgrade and improvement in the indoor thermal comfort conditions that strongly influence the health and well-being of building users. It also leads to lower energy usage by the buildings; lower the energy bills and thus lower the risk of energy poverty of the society [39].

The urgent need for thermomodernization in order to improve the energy parameters of buildings in Poland has been stated in conducted studies, survey research, and legal acts. According to the National Population and Housing Census of 2011 [40], around 72% of the buildings in Poland were built before 1989. This rate dropped to 59% in 2021 [41]. According to a study conducted in 2018 on a group consisting of 35.4% of the residential buildings in Poland [42], 39.3% multifamily residential buildings were in crucial need of thermomodernization to adjust their technical condition to modern energy performance standards. Economically viable thermomodernization regarding residential buildings would allow for a reduction of energy demand by 75% as well as a reduction of greenhouse gas emissions by around 10% [33]. Buildings built before 1945 deserve special attention, as the average useable energy consumption for heating exceeds 200 kWh/(m^2 year) [17]. They are often characterized by rich architectural details, represent cultural heritage, and constitute a significant group of buildings in strict city centers. According to the report conducted in Wroclaw (Poland) in 2019 [43], 21% of residential premises of the studied population were located in multifamily buildings built before World War II. The pre-war buildings are characterized by poor thermal properties and thus high energy demand for heating in cold and transition periods. The noticeable progress of thermomodernization technologies and, simultaneously, the tightening of European regulations on energy consumption in buildings also lead Poland to support the modernization process, the monitoring of the technical conditions of the housing stock, and the enhancement of energy efficiency and improving the living conditions of society [33,44]. Improvements of the energy parameters can be achieved by introducing modifications into the building envelope since its design and materials parameters significantly influence its energy performance. The research conducted on tenement buildings in Wroclaw [17] indicated that the window exchange can bring about 16% in energy savings when the whole building is analyzed; an additional 15% can be achieved by external wall insulation and 14% when the roof is thermomodernized, and additional internal insulation can bring an extra 15%. However, the achieved savings vary significantly when apartments are considered individually.

Today, to predict and evaluate energy use and indoor climates, Building Energy Modelling (BEM) is often applied. An energy consumption prediction model can be acquired through a data-driven study (black-box model) or a physical model (also known as white-box model). While data-driven building energy consumption prediction models do not rely on detailed energy modelling and analysis, a physical model calculates building energy consumption given that detailed building and site parameters are defined in the building energy simulation software [45]. La Fleur et al. [46] used a BEM model created in IDA ICE version 4.6.2 and concluded that energy demand can be reduced by 44% after renovation. Nadeem et al. [23] applied EnergyPlus to carry out energy simulations for a reference house in different climate conditions. Other examples of software appropriate for physical models include eQuest [5], EnergyPlus, BEopt v.2.8.0.0 [10], WUFI Plus v.3.2.0.1 [47], and Ecotect [48]. The majority of the research and analysis focuses on modern apartment or office buildings. There is a shortage of studies on buildings' energy consumption predictions concerning pre-war residential construction, which is particularly common in Poland. In addition, there is a lack in the literature describing research on buildings located in Europe in a temperate climate. Much of the literature describes activities carried out in the eastern part of Asia, mainly in China and South Korea.

The purpose of this article is to present an analysis of the indoor parameters and energy consumption for heating purposes for an apartment located in a pre-war tenement building before and after thermomodernization based on measurements and simulation software. The analyzed building is located in the center of Wroclaw, Poland. Apart from energy consumption monitoring, indoor temperature, surface temperature, and external temperature were also recorded during the whole research period. To predict the indoor thermal environment and energy consumption in the apartment, WUFI Plus v.3.2.0.1, an energy simulation software, was also applied. The article focuses on a building existing in real conditions and fills a gap in the literature that lacks information on analyses covering individual apartments in pre-war tenement houses located in a dense urban tissue in a moderate climate, information on the possibilities and limitations of thermal modernization activities, actual information on energy consumption before and after thermal modernization, and the prediction of potential energy savings after applying additional possible modernization measures that could bring tangible benefits to residents.

2. Apartment Characteristics

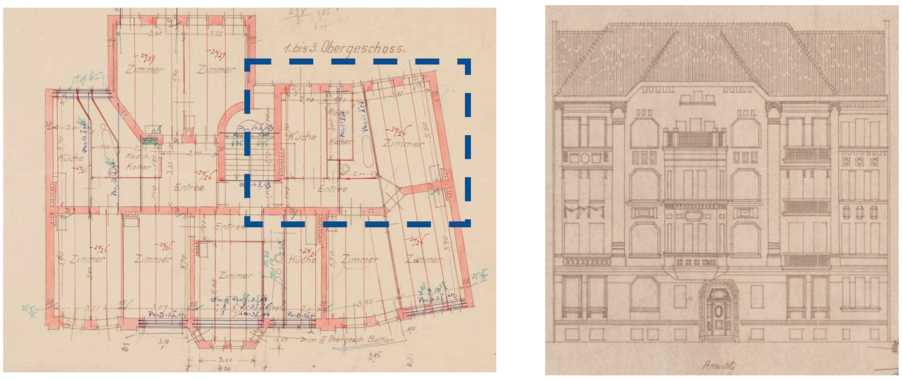
2.1. Location and Apartment Characteristics

The analyzed flat is located on the first floor of a five-story tenement house placed in the dense urban center of Wroclaw, Poland (Figure 1). The building was built before the Second World War in 1910. The original layout and façade of building [49] are presented in Figure 2. The analyzed space is located on the back side of the building.

Originally, the investigated space was a part of the larger flat; however, during the Second World War, the building was demolished and rebuilt after the war. Therefore, the final arrangement of the building's internal space and the size of the flat changed. The final layout is presented in Figure 3a.

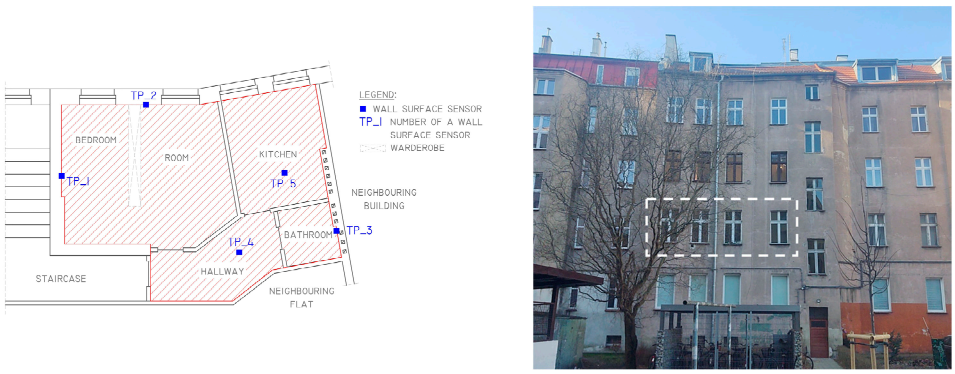
The investigated studio apartment is located on the intermediate floor (Figure 3b). The space area is around 42.6 m^2 with a height reaching 3.25 m. It is divided into a main room, kitchen, bathroom, and hallway. The neighboring areas of the investigated studio include a staircase, another flat, and residential areas in the adjacent building. The apartment is naturally ventilated and has only one external wall oriented northeast with four large windows facing the backyard of the building. This direction negatively influences the amount of sunlight delivered to the flat and thus the amount of sun gains and internal conditions during the year. This effect is enlarged by the nearby building situated opposite to the investigated building, as presented at street plan in Figure 1.

Figure 1. The Google map view of the tenement building (blue dashed line) with the investigated flat location marked in red.



(**a**) (**b**)

Figure 2. Original technical drawings of the building (1910) [49]: (**a**) layout of the 1st–3rd floors with the location of the analyzed space marked (dashed line); (**b**) façade.



(**a**) (**b**)

Figure 3. The building today: (**a**) the layout of the of the analyzed flat with designations of internal surface sensors: Tp_1—temperature of the staircase wall, Tp_2—temperature of the external wall, Tp_3—temperature of the wall of the neighboring apartment (another building), Tp_4—the slab temperature, Tp_5—the floor temperature; (**b**) the backyard elevation, investigated flat with windows are marked by dashed box.

The investigated flat is naturally ventilated. Two exhaust grills are mounted in the kitchen and bathroom (Figure 3a). The heating system consists of five radiators mounted under the windows and in the bathroom, supplied with hot water prepared in an old open-chamber gas boiler located in the bathroom.

The apartment originally was occupied by an elderly person who preferred lower temperatures for reasons of energy conservation and habit; therefore, during the heating period, the indoor temperature was maintained mostly at 18 and 17 °C. Later, the windows in the apartment were exchanged for triple-glazed, the heating system was exchanged, and a higher heating set point temperature was defined.

2.2. The Construction of Building Elements before the Thermomodernization

The tenement house is a traditional pre-war construction. The walls are made of brick and traditional plaster with an additional air cavity in the exterior walls. The original brick ceiling remains only above the basement while the rest of the interior slabs are constructed of concrete and tuff covered with timber flooring. The U-values for the walls and slabs were calculated following their construction.

The original windows were in poor technical condition. Their construction was traditional for pre-war tenement houses, namely, single-glazed in a wooden casement double box. Considering the above and the subsequent Polish Standard of 1957 [50], the U-value coefficient was defined at 5 W/(m^2K) for the analysis.

The thermal transmittance coefficients of the building elements are presented in Table 1.

Table 1. Thermal transmittance of the building elements.

Building Element	Additional Area	Area	Thermal Resistance	U before Thermo-Modernization
		m^2	m^2K/W	W/(m^2K)
External wall	outdoor	17.03	0.812	1.02
Windows	outdoor	9.2	-	5.00
Internal wall IW1	staircase	27.45	0.65	1.10
Internal wall IW2	neighbors	39.82	0.25	1.96
Internal wall IW3	the same flat	32.63	0.15	2.44
Slab (ceiling)	neighbors	45.4	0.699	1.11
Slab (floor)	neighbors	45.4	0.699	0.96

2.3. The Construction of Building Elements after the Thermomodernization

The choice of thermomodernization measures must be preceded each time by a technical and financial analysis, taking into account local regulations, restrictions arising from the location of the object (e.g., the guidelines of the conservation office and the division of land property), as well as the division of ownership of the building, the plans of the tenement community, and the financial issues. After the deep analysis, the partial thermal modernization of the apartment consisted of the replacement of the windows for modern triple-glazed, with a U-value of 0.9 W/(m^2K), and the replacement of the old heat source to a new, highly efficient gas boiler with a closed combustion chamber. An additional argument for completing such a scope of thermal modernization was the receiving of financial subsidy from the authority for the carried-out measures.

2.4. The Thermomodernization Options Defined for Energy Simulations

Further steps to analyze the possibility of reducing the energy consumption by thermomodernization of the apartment required the use of energy simulation software: WUFI Plus. The first step was to exchange all windows to triple-glazed with a U-coefficient of 0.9 W/(m^2K) and the apartment door for a modern one, insulated with a U-value of 0.86 W/(m^2K). Option 2: adding perlite filling to the cavity in the exterior wall, giving a total U-value of the external wall of 0.32 W/(m^2K). Option 3 considered an additional

20 cm of external polystyrene wall insulation, which gave a total (with former perlite layer) external wall U-value of 0.12 W/(m^{2}K). The last option took into account the insulation of the wall between the apartment and cold staircase and led to a decrease in the final value of U-value equal to 0.68 W/(m^{2}K). The aforementioned stages of possible thermomodernization measures were proposed, taking into account feasible technical, financial, and legal issues that the owner could implement on his own independent initiative. Only the external insulation of the exterior wall (Option 3) could not be implemented individually; it was planned to be realized in the future by all co-owners of the tenement building.

Table 2 below presents the new U-coefficients and compares them with those defined in the Polish Regulations [3] dedicated for new constructed buildings.

Table 2. U-values for building elements.

Building Element	U-Value after Thermomodernization	U-Value from Polish Regulations [3]
	W/(m^{2}K)	W/(m^{2}K)
Windows	0.9	0.9
Entrance door	0.857	1.3
External wall (Option 2)	0.317	0.2
External wall (Option 3)	0.115	0.2
Internal wall (between the staircase and the apartment)	0.682	0.3

3. Measured Data

The measurements in the investigated apartment were conducted between 21st November 2021 and the end of January 2022. The external temperature was measured by a Testo 176 T1 data logger (by Testo SE & Co. KGaA, Titisee, Germany) with an integrated Pt100 sensor (measuring range: –35 to +70 °C; accuracy: ±0.2 °C). To assess the indoor conditions of the apartment, the indoor temperature in all rooms and surface temperatures were measured. The values of the internal and surface temperatures were gathered by the TESTO 175-T2 with internal NTC sensor (measuring range: –35 to +55 °C; accuracy: ±0.5 °C), equipped in a wall surface temperature NTC probe (measuring range: −50 to +80 °C; accuracy: ±0.2 °C for the range of −25 to +80 °C). The measuring equipment for air temperature and surface temperature used for the research follows the restrictions of International Organization for Standardization: ISO 7726 [51].

The values of heating set point temperature and gas consumption were gathered by individual readings during the investigated periods. The natural gas usage was monitored via individual gas meter G4 RF 1 by Itron Inc. (Liberty Lake, WA, USA), (measuring range: 0.04 to 6 m^3/h; typical gas flow rate: <2 dm^3/h; maximum permissible measurement error: ±1.5% for the average range of 0.1 Q_{max} and Q_{max}; class 1.5) [52]. The gas meter meets the European Standard 1359 Measuring Instruments EU Directive (MID) and Polish legalization requirements [53] for use by companies measuring and supplying natural gas to the individual customer.

The set point temperature was defined at the wall-mounted controller located in the apartment.

4. Results of Measurements

4.1. Indoor Conditions and Energy Usage before Thermomodernization

During the measuring period, the external temperature was relatively high for this time of the year with an average value of 2.6 °C (M_e = 2.25 °C, SD = 4.02 °C). The highest and the lowest values, +14.7 °C and −10 °C, occurred on the last days of December and the beginning of 2022, respectively. The variation in measured external temperature (Te), indoor temperature for every flat space (T) and wall, and slab and floor temperature (Tp) are presented in Figures 4 and 5, respectively. The whole measured period was divided into five individual periods according to the heating set point temperature, namely, A—17 °C, B—18 °C, and C–19 °C, as presented in Figures 4 and 5. These set points varied and were settled much below the comfort temperature for living residential spaces. Their levels were established by the elderly owner living in the apartment.

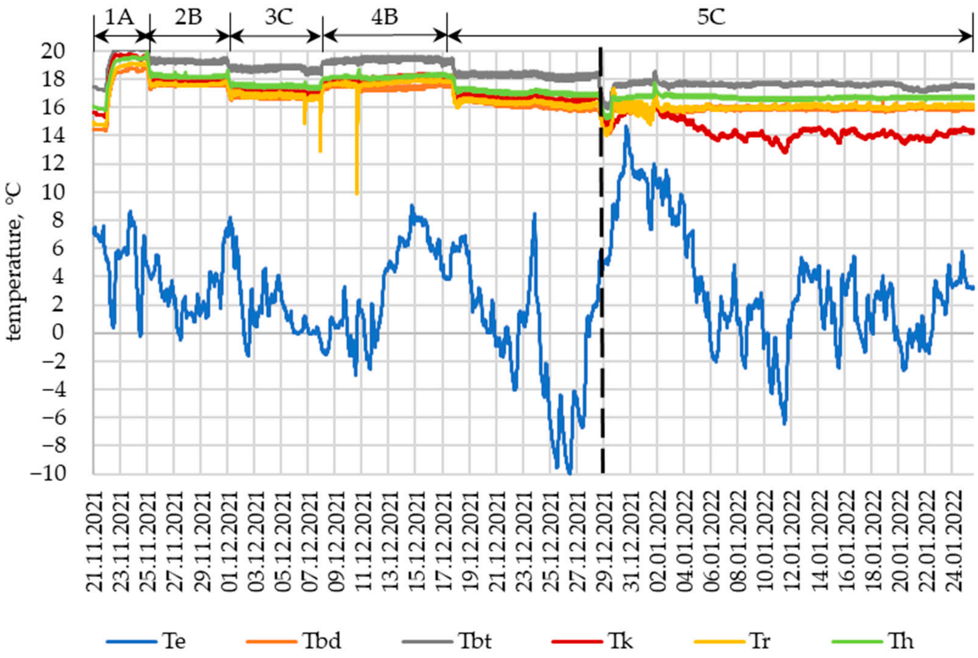


Figure 4. The variation in measured external (Te) and indoor air temperature for every flat space, namely, Tbd (bedroom temperature), Tbt (bathroom temperature), Th (hallway temperature), Tk (kitchen temperature), and Tr (main room temperature); A, B, and C indicate 5 periods with different heating set points (Tsp): A—Tsp = 19 °C, B—Tsp = 18 °C, C—Tsp = 17 °C.

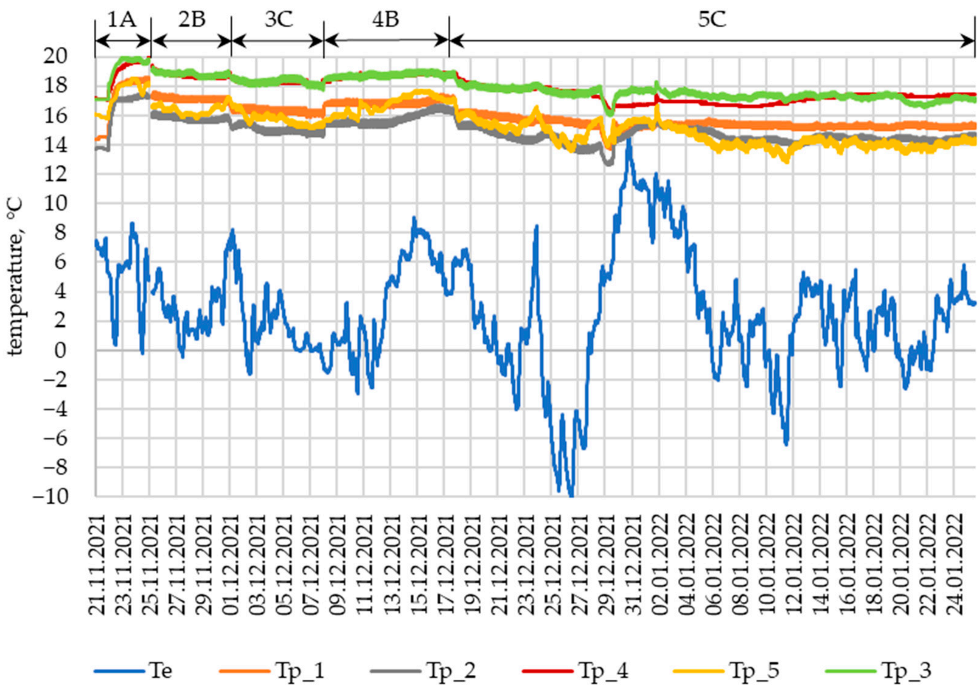


Figure 5. The variation in measured external (Te) and surface temperature: Tp_1—temperature of the staircase wall, Tp_ 2—temperature of the external wall, Tp_3—temperature of the wall of the neighboring apartment (another building), Tp_4—the slab temperature, Tp_5—the floor temperature; A, B, and C indicate 5 periods with different heating set points (Tsp): A—Tsp = 19 °C, B—Tsp = 18 °C, C—Tsp = 17 °C.

During the whole measuring period, the indoor temperature was stable and oscillated around heating set points. Period 1 (1A) presents the visible rapid change in temperature with the highest set point of 19 °C, and it is considered as a pre-heating time of the apartment after longer absence of the owner. During periods 2B and 4B, the interior temperature had been set to 18 °C which thus was the observed indoor temperature. In the remaining measuring periods, the heating set point was defined as 17 °C. The weighted average set point temperature was calculated to be 17.3 °C (SD = 0.59 °C) for the whole measuring period.

The closest air temperature to the set point was recorded in the hallway, which is a fully internal space with only a small area connected with the wall and door from the staircase side. This is also the space where the heating controller is installed. The air temperature in the bathroom is slightly higher as it is a fully internal space, where the old type of non-insulated gas boiler with an open combustion chamber was located. The temperature patterns in the remaining rooms follow the heating set point; however, the influence of the external wall and windows is clearly visible. The effect of opening the window, when there is a rapid and short decrease in the measured indoor temperature, can be seen in Figure 4 in periods 3 and 4. The exception is the variation in temperature in the kitchen starting from 29 December. This effect was probably caused by an intake of external air by opening the unsealed ventilation grill mounted in the external wall straight under the window. This variation in the indoor air temperature coincides more strongly with the change in external temperature than other readings.

The highest values of surface temperature occurred in the inner area of the apartment, namely, in the bathroom and hallway (Tp_3 and Tp_4, respectively); the lowest occurred on the inner side of external wall (Tp_2). The temperature of the floor was expected to be higher, as below it is another apartment; however, the measurements indicated that it was as cold as the surface of the external wall.

The relationship between external temperature, set point temperature, and the gas usage for heating purposes is presented in Figure 6. The gas consumption was a background to estimate the energy consumed for heating purposes by the apartment.

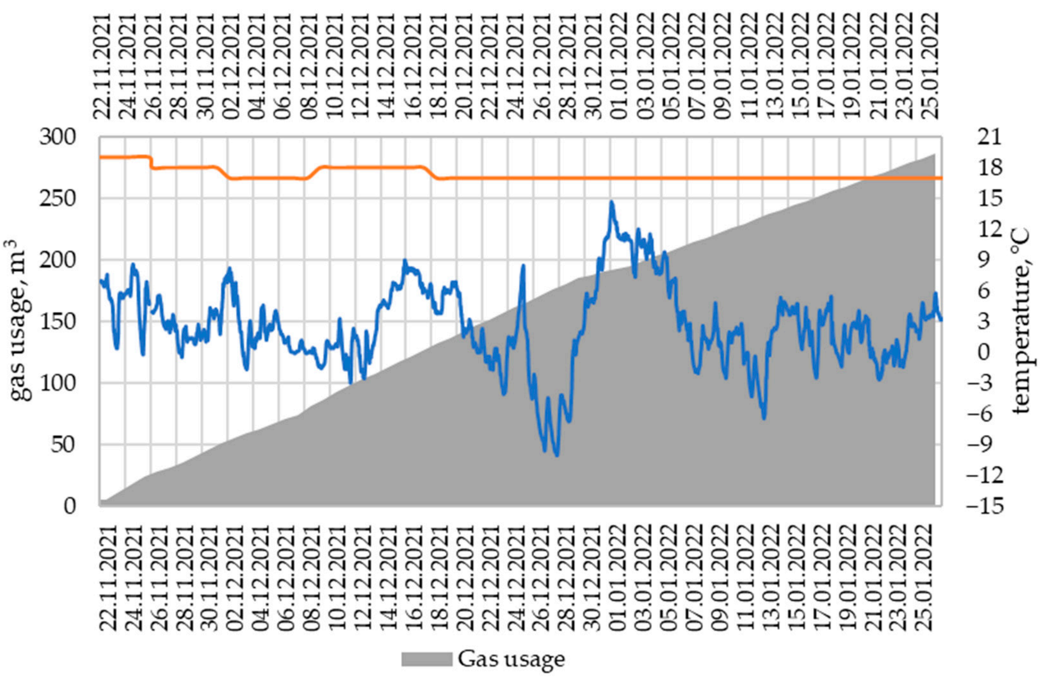


Figure 6. External temperature (Te), set point temperature (Tsp), and cumulative gas consumption for heating purposes during the investigated period.

Between 21 November and 26 January 2022, about 281 m^3 of natural gas from the city network was consumed to heat up the apartment. The total gas consumption for each measuring period is presented in Table 3. The accuracy of the gas and energy consumption readings are the equivalent and are based on the accuracy of the gas meter, namely, ±1.5% for the average flow rate. Table 3 also presents the mean external temperature for the investigated period with the calculated median (M_e) and standard deviation (SD) of the parameter.

Table 3. The real energy consumption for heating purposes of the investigated apartment.

No. of Reading	Date of Reading	No. of Days	Heating Set Point	Gas Meter Reading	Gas Consumption	Final Energy Consumption	Usable Energy Consumption	Mean External Temperature	Median	Standard Deviation
			°C	m^3	m^3	kWh	kWh	°C	°C	°C
1	22 November 2021	1	19	5.684	0.3	3	2.1	6.38	6.80	0.89
2	25 November 2021	3	18	24.661	19	214	141.5	4.77	5.60	2.50
3	28 November 2021	3	18	35.441	11	121	80.4	2.66	2.67	1.50
4	1 December 2021	3	17	51.538	16	181	120.0	3.32	2.76	2.06
5	7 December 2021	6	17	74.509	23	259	171.2	1.92	1.57	2.99
6	8 December 2021	1	18	80.92	6	72	47.8	−0.27	−0.01	0.56
7	11 December 2021	3	18	98.079	17	193	127.9	0.26	0.53	1.33
8	17 December 2021	6	17	127.066	29	326	216.1	4.81	5.86	3.05
9	29 December 2021	12	17	185.525	58	658	435.8	−0.14	0.64	4.64
10	2 January 2022	4	17	195.233	10	109	72.4	10.29	11.01	2.28
11	26 January 2022	24	17	286.355	91	1026	679.3	2.11	2.11	3.19

Energy consumed by the apartment was calculated following the reading of the gas meter and the conversion factor provided by the gas company. During the analyzed period, the coefficient equaled 11.258 kWh/m^3.

The weighted average heating set point temperature in the investigated period was 17.3 °C, and the total energy consumption was 3163 kWh. It gave the average daily consumption of 48 kWh/day (4.3 m^3 per day) with a mean external temperature about 2.6 °C (M_e = 2.25°C, SD = 4.02 °C).

The recorded values were later compared with the energy consumption after the partial modernization of the apartment.

4.2. Indoor Conditions and Energy Usage after Thermomodernization

After the partial retrofit of the apartment (window and gas boiler exchange), the average daily energy usage dropped to 20 kWh/day (1.8 m^3 per day of natural gas) for the indoor temperature set point of 18 °C. This means that only the exchange of windows and replacing the old gas boiler with a new and more efficient one created over 57% of savings in energy consumption while maintaining about a 0.7 °C higher average heating set point temperature.

Following the further measurements, while the set point was settled by new owners between 21 and 22 °C and, simultaneously, the gas was also used for domestic hot water (DHW) preparation and cooking purposes, the energy usage was still smaller than before the thermomodernization (when the only heating system was supplied by the gas network) and reached a maximum of 32 kWh/day (about 2.7 m^3 per day of natural gas).

The relationship between gas consumption in m^3 before and after the apartment thermomodernization is presented in Figure 7. The graph shows the change in the slope of the trend function toward the reduction in gas consumption for the studied premises. The change is visible even when the indoor temperature is kept on higher levels.

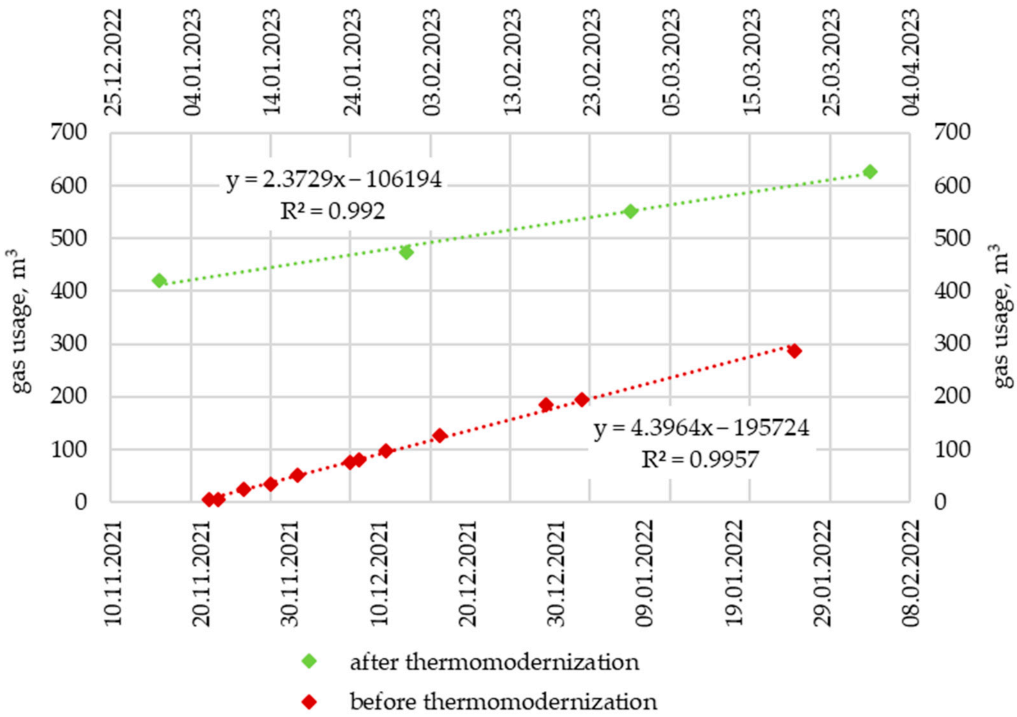


Figure 7. The gas consumption trends before and after thermomodernization.

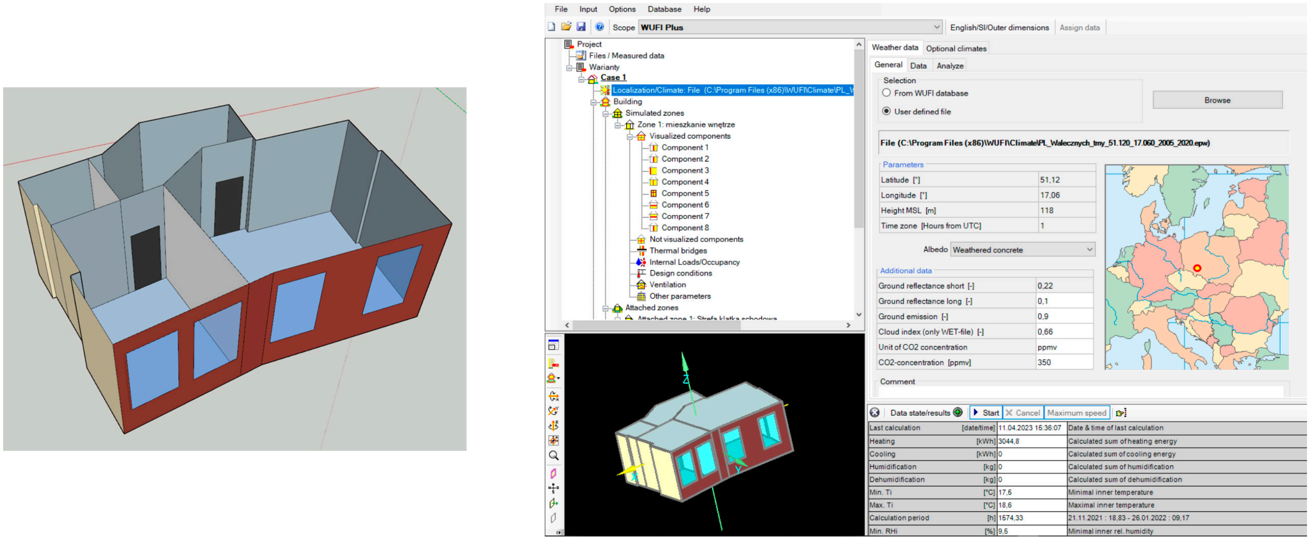
Figure 7 clearly illustrates the shift in the trend function slope, indicating a decrease in natural gas consumption for the examined flat. This change is noticeable even when maintaining a higher heating set point temperature and using additional gas for DHW and cooking purposes.

5. Energy Simulations of the Investigated Apartment

Deeper analyses leading to a reduction in energy usage for heating by the apartment were undertaken in the whole-year building simulation software WUFI Plus. The geometry of the investigated flat was created in SketchUp software and then exported to WUFI Plus where all the boundary conditions were defined and energy calculations were performed. The created model geometry of the apartment is presented in Figure 8.

To undertake energy simulations, it is necessary to define weather data for the investigated location. Due to the lack of some parameters, while only the external temperature was monitored, it was not possible to create a data file based on the measured values; therefore, the needed outdoor climate data were imported from the Meteonorm database with statistical values interpolated for the investigated location.

The variability of the external temperature for the whole research period is presented in Figure 9 below. The measured data are presented as a blue line, and the statistical data, interpolated from Meteonorm, are presented as the orange line. It is clearly visible that the biggest discrepancies between measured and average values occurred in the second half of the measuring period (end of December and January).



(**a**) (**b**)

Figure 8. Analyzed apartment: (**a**) model geometry of the investigated apartment (SketchUp); (**b**) WUFI Plus editing window (the red circle indicates the location of the investigated building on the map).

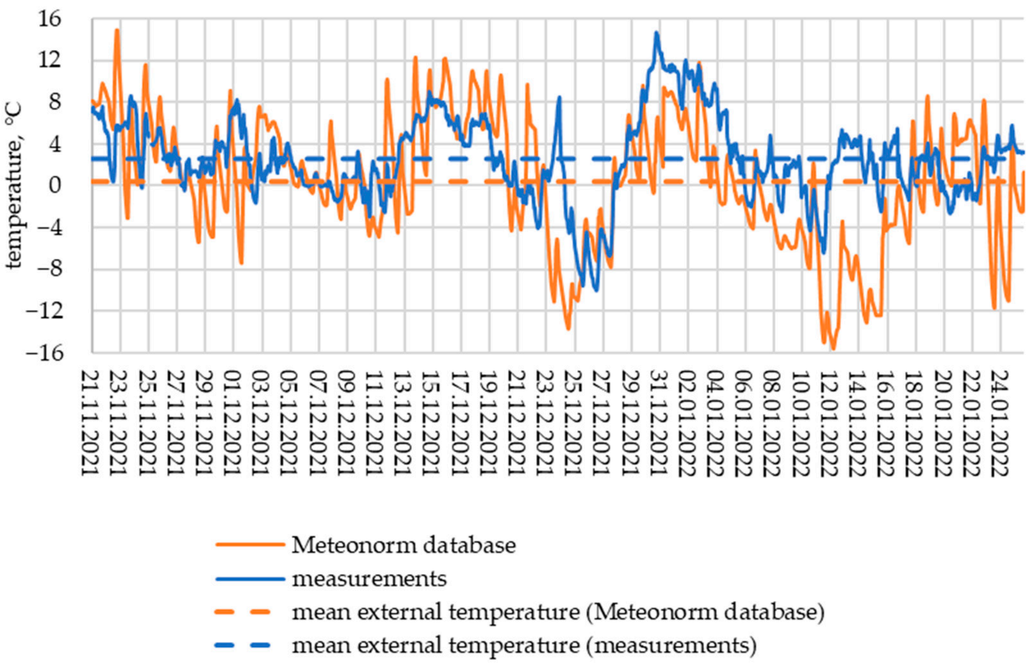


Figure 9. External temperature recorded by the data logger (blue line) and exported from Meteonorm (orange line) for the whole research period.

While the statistical weather data were implemented in WUFI Plus software, the first step to create the simulation was to match the WUFI model to the real conditions in the monitored period. The parameter that can be compared in both cases is useable energy for heating. The energy calculated from the gas usage is a final energy; therefore, it was necessary to recalculate it into usable energy. This was performed by taking into account the overall efficiency of the system calculated following the Polish Regulations on building certificates [54] following the equation:

$$Q_{k,H} = Q_{H,nd} / \mu_{H,tot}, \quad (1)$$

where: $Q_{k,H}$—final energy; $Q_{H,nd}$—usable energy; and $\mu_{H,tot}$—total efficiency.

The total efficiency takes into account the efficiency of heat generation, accumulation, transportation, and regulation. For the investigated case, the seasonal average efficiency of 66.2% was calculated by multiplying the seasonal average efficiencies:

- Heat generation $\mu_{H,g}$—gas or liquid fuel boilers with an open combustion chamber (atmospheric burners) and two-state regulation of the combustion process: efficiency of 0.86;
- Accumulation $\mu_{H,s}$—no accumulation vessel: efficiency of 1;
- Transportation $\mu_{H,d}$—residential heating (heat production in the space of a residential premises): efficiency of 1;
- Regulation $\mu_{H,e}$—water heating system with section or panel radiators in the case of central regulation without automatic local regulation: efficiency of 0.77.

This final value was a background to calculate the usable energy for the pre-thermomodernization state. The usable energy calculated from the real gas usage in the investigated period was 2092.4 kWh.

To create the realistic simulation for the statistical weather database, the validation of the model was necessary. Therefore, certain steps to match the model to real conditions were taken. The first approach assumed the constancy of a transmission heat loss coefficient, i.e., H_T = const. The calculated value for the design conditions was determined as 75.2 W/K, and thus, the ventilation heat loss coefficient was estimated. Finally, to match the simulation model to the measured conditions, the heat loss coefficient was determined as 58 m^3/h as presented in Figure 10 below, which gave an infiltration rate of about 0.5 h^{-1} (consisted with the European Standard [55]) and thus a usable energy of 2093.80 kWh.

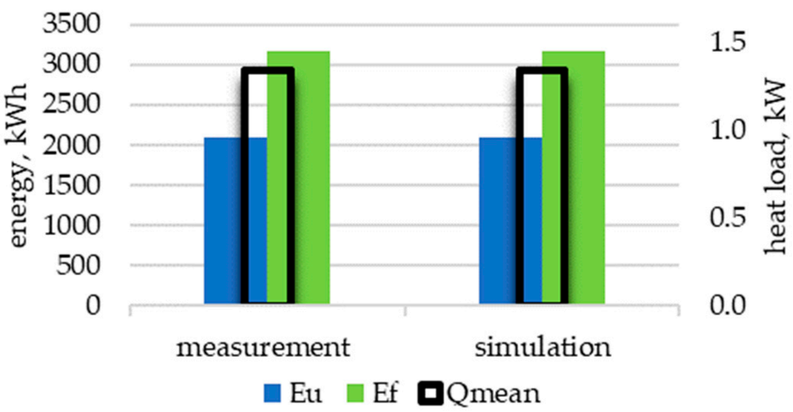


Figure 10. Model adjustment to the real conditions. Eu—usable energy, Ef—final energy, Qmean—mean heating load.

The WUFI Plus analysis of the apartment before the thermomodernization gave the final energy (Ef) usage in the investigated period of 3159.8 kWh, while the energy usage calculated from the gas utilization by the apartment was 3161.9 kWh.

5.1. Pre-Thermomodernization Simulation Analysis

The variations in simulated temperature before the thermomodernization are presented in Figure 11 below. The most sensitive parameter to changes in external temperature is the window surface temperature. Its variability follows the change in outside air temperature. This similarity is caused by the poor thermal characteristics of old windows, i.e., their very high heat transfer coefficient of 5 $W/(m^2K)$ and thus low thermal resistance.

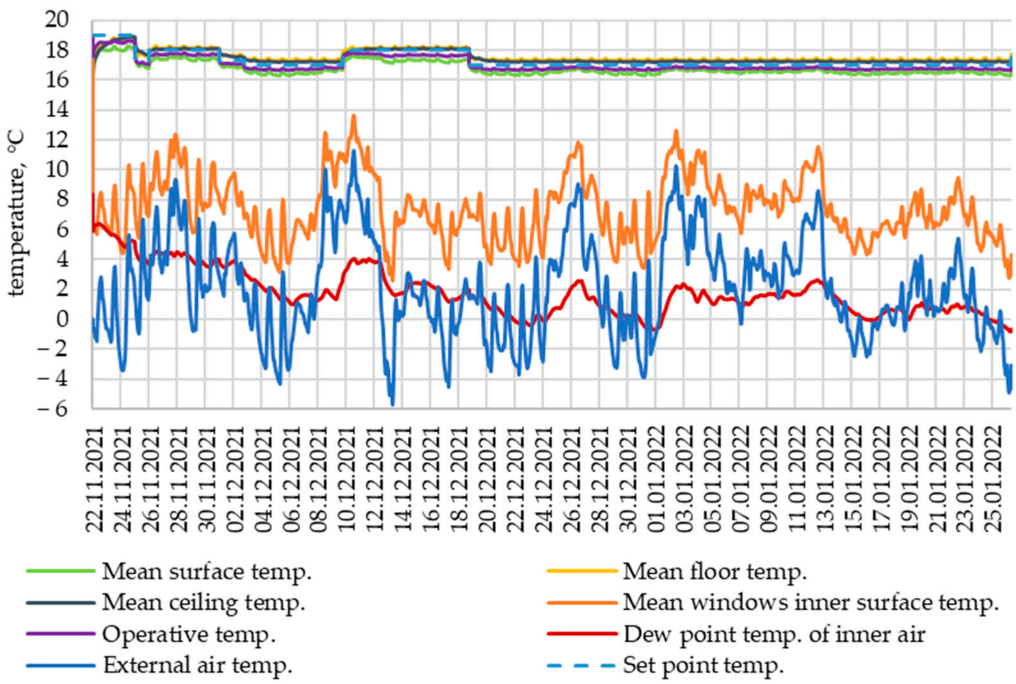
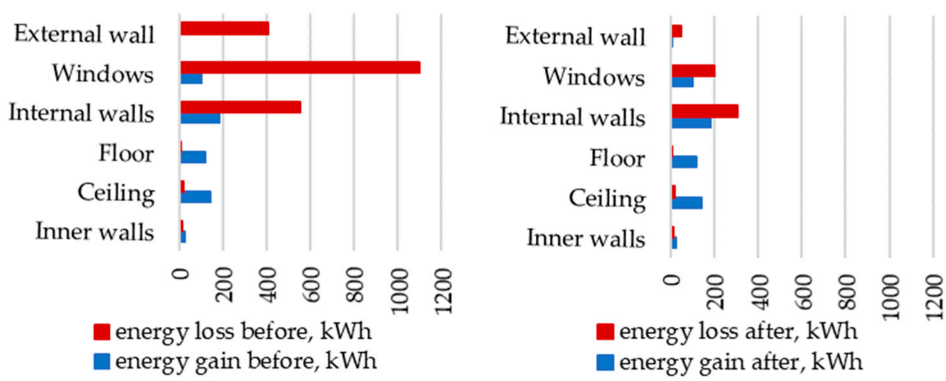


Figure 11. Temperature variation during the investigated period (before thermomodernization).

These building elements cover the significant area of external façade, namely, 9.2 m^2 in comparison to 17 m^2 of external wall. It gives over 35% of the total area of the external envelope of the apartment and therefore causes a significant loss via conduction. The share heat losses via windows in total static losses via external façade reach over 70%. This relationship is presented in Figure 12a.



(**a**) (**b**)

Figure 12. Simulation results—energy gains and losses in kWh: (**a**) before the thermomodernization and (**b**) after the thermomodernization (option 4).

Low temperatures of inner surfaces are potentially risky in terms of moisture condensation. Therefore, it is important to check if the surface temperature does not drop below the dew temperature. For the investigated case, based on the statistical Meteonorm database of external weather conditions and the mean internal parameters of 17.3 °C and 35.3% RH, only the period between 22 and 24 November indicates the possibility of moisture condensation problems on the inner window surfaces (Figure 11).

Due to the apartment's exposure to the northeast, negligible solar gains are observed (Figure 12). They also do not affect the temperature profiles of the interior surfaces of the exterior wall and windows (Figure 11). The temperature of the remaining surfaces of inner building elements follow the changes of the heating set points.

5.2. The Simulation Analysis of Thermomodernization Options

The second set of simulations in WUFI Plus was conducted after the building thermomodernization to check the change in energy consumption of the apartment after the addition of the chosen thermomodernization actions. The thermomodernization actions also resulted in a significant change in the temperature variation of the building elements (Figure 13). The difference between the state before and after improvements is strongly visible on the window surface temperature pattern. After lowering the windows' U-value to 0.9 W/(m^{2}K), their surface temperature did not drop below 14.5 °C, even under the lowest external temperature. Considering this, the risk of surface moisture condensation of the external elements did not occur.

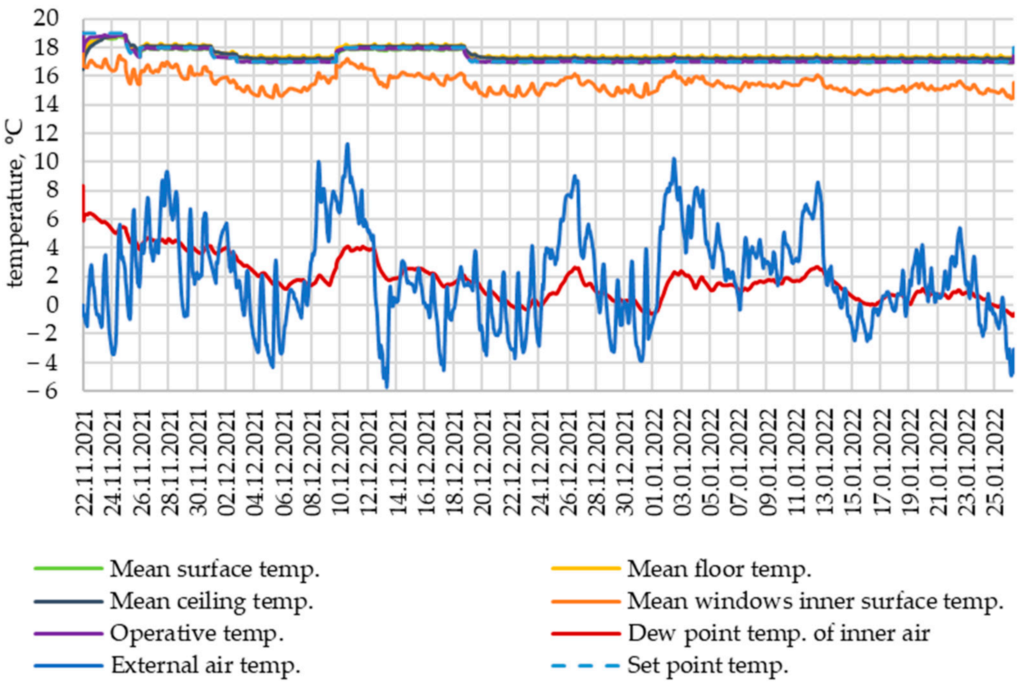


Figure 13. Temperature variation during the investigated period (after thermomodernization —option 4).

All thermomodernization options are described in detail in Table 4, where the simulation results for each option are presented in the form of useable and final energy consumption. The useable energy losses via the building elements for thermomodernization option 4 are also presented at Figure 12b and compared with the pre-thermomodernization state (Figure 12a). The modernization of heating system consisted of exchanging the radiators, mounting thermostatic valves, and exchanging the heat source for modern, highly efficient gas condensing boiler.

The new average efficiency was calculated following the seasonal average efficiencies [54]:

- Heat generation $\mu_{H,g}$—condensing gas boilers (70/50 °C) with nominal power up to 50 kW: efficiency of 0.91;
- Accumulation $\mu_{H,s}$—no accumulation vessel: efficiency of 1;
- Transportation $\mu_{H,d}$—residential heating (heat production in the space of a residential premises): efficiency of 1;
- Regulation $\mu_{H,e}$—water heating system with section or panel radiators in the case of central regulation and local with a thermostatic valve with proportional band of P—2 K: efficiency of 0.88.

Table 4. Energy consumption for different thermomodernization options.

Option No.	Description of Thermomodernization Action	Usable Energy	Final Energy with Existing Heating System	Final Energy with Modernized Heating System
		kWh	kWh	kWh
Base option	before the thermomodernization	2093.8	3161.9	-
Option 1.1	windows	1192.1	1800.2	1490.1
Option 1.2	windows + entrance door	1121.2	1693.1	1401.5
Option 2	windows + entrance door + cavity insulation of external wall	883.6	1334.3	1104.5
Option 3	windows + entrance door + cavity insulation of external wall + external insulation of external wall	764.2	1154.0	955.3
Option 4	windows + entrance door + cavity insulation of external wall + external insulation of external wall + insulation of internal wall (between the staircase and the apartment)	590.6	891.9	738.3

Finally, the average efficiency of the new system was 80% and measurably contributed to the reduction in the final energy value of the apartment (Table 4).

The undergone upgrades resulted in a measurable effect in useable and thus final energy. The exchange of the existing windows without exchanging of the heating system gave a significant change: over 43% in final energy consumption. Additional external wall insulation, depending on the method applied, affected an additional 17%. More savings were obtained by exchanging the apartment door, adding insulation on the internal wall, and exchanging the existing heating system. Finally, the energy savings reached over 70%, which is presented in Figure 14.

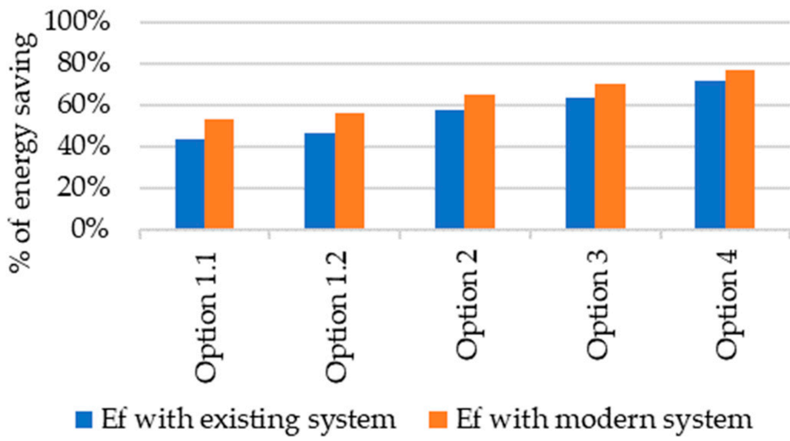


Figure 14. Calculated percentage of energy savings (in kWh) for different thermomodernization options with (blue) and without (orange) modernization of the heating system.

For the investigated apartment, in the terms of flat energy consumption, the wall and window insulation level is crucial (Figures 12 and 15); however, in terms of moisture condensation risk and comfortable indoor conditions, mainly window U-value is crucial due to the importance of inner surface temperature, which is presented in Figures 11 and 13.

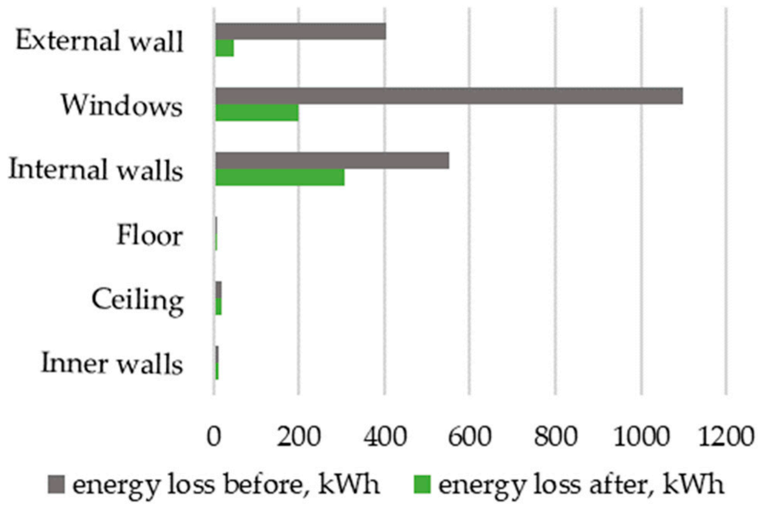


Figure 15. Energy loss via different building components before and after thermomodernization of the heating system (option 4).

6. Conclusions

Existing and especially very old buildings have great potential in efforts to save energy. While many studies focus on theoretical considerations of whole premises and office buildings, the article fills the gap and focuses on a feasible solution for a single apartment in a residential building built before World War II located in Wroclaw, Poland, where the thermomodernization possibilities are limited due to technical, legal, social, and economic factors. The analysis focuses on the winter season and heating, as a majority of such buildings are not equipped in air conditioning or mechanical ventilation systems. The measures implemented in practice were based on the owner's technical and financial capabilities, without requiring the approval of the housing community. The proposed additional measures included in the simulation analyses could have been taken by the owner on his own independent initiative, or, as in the case of exterior wall insulation, measures that the housing community planned to implement in the future.

Variability in indoor temperature and energy consumption was shown for the apartment before and after thermomodernization following the measured data. The results of energy simulations for the investigated apartment were presented, which, after the implementation of thermomodernization measures, resulted in a positive effect in the context of both thermal comfort and energy consumption.

The obtained results showed that due to the fact of the high WWR (window–wall ratio) and window U-value, the most efficient thermal modernization measure leading to lower energy consumption and increased indoor comfort was window replacement. In the investigated apartment, windows covered over 35% of the total area of the external envelope and caused about 70% of static losses via the external façade before the thermal modernization. The window exchange resulted in more than 43% of the final energy savings, while with the modernization of the old, inefficient heating system, this value raised to the figure about 53% in simulated and 57% in real conditions. The energy simulation of additional actions indicated lower individual benefits, resulting in total savings of up to about 70% (77% with heating system modernization) in the final energy consumption. An important fact is that a higher heating set point was maintained after thermal modernization, which also had an impact on the increasing energy consumption by the apartment. Despite the higher temperature setting in the apartment, reaching as high as 21–22 °C (before the thermomodernization, the average set point temperature equaled 17.3 °C), gas consumption for heating was lower than before thermomodernization.

To maintain the proper thermal comfort level in residential flats, it is important that a minimum temperature of 20 °C indoors should be maintained (the mean radiative temperature and air temperature should be similar). In the analyzed case, the level of thermal comfort was lowered compared to technical standards. However, in such non-modernized buildings in Poland, inhabited mostly by elderly people, lowering the set point temperature results from economic reasons.

In the investigated case, due to the northeast orientation of the apartment, the solar gains are negligibly small, and thus so is its impact on energy consumption.

The additional benefit of window replacement with those with higher thermal resistance is that their surface temperature is higher, avoiding surface condensation. This also has a positive effect on improving interior conditions with a higher mean radiant temperature and thus improved thermal comfort of the residents.

The presented analysis showed the importance of retrofit measures and proved that even a small improvement can bring significant benefits in the field of energy and thermal comfort.

While long-term research on occupied private apartments is difficult to conduct, it is recommended to use dedicated energy simulation software. In the article, WUFI Plus v.3.2.0.1 was applied to estimate the energy usage before and after thermomodernization of the apartment and to check the possible savings when more complex thermal modernization solutions were applied. Additional measures described as options 1.2 to 4 were analyzed for both the existing and modernized heating system.

The created model needed some simplifications and validation due to several factors: the lack of full data of external conditions and thus the application of statistical data (e.g., Meteonorm database) as well as difficulty in defining air rates of natural ventilation or the impact of residents on indoor conditions. Despite the aforementioned issues, the simulations show a good representation of the apartment behavior in real conditions before and after building thermomodernization.

The engineering programs to simulate building energy consumption and potential savings approaches are effective engineering tools. They are a powerful and very helpful tool for predicting energy consumption and determining the comfort level of users. However, each case should be considered individually on a case-by-case basis, as there is often a lack of technical documentation and many unknowns in this type of building, leading to problems in the accurate representation of the building's operation and performance and thus discrepancies in the results of the simulation and reality.

In order to reduce the energy consumption and increase the indoor comfort in individual apartments, it is recommended to start the thermal modernization by replacing windows with those with a low U-value and, when the WWR is favorable, also insulating external walls. After reducing energy demand, it is recommended to exchange the inefficient heating system that contributes to the final energy consumption and thus high heating costs. The thermomodernization of the roof or the slab beneath unheated attics is recommended for apartments located on the highest floors or when the whole building is being considered [17].

In future research, it is advisable to look closer for the economic analysis and environmental effects. As window and inefficient heating system replacement undeniably brings tangible benefits, it is recommended to conduct economic analyses of additional further modernization measures as well. Due to the recent energy crisis, this could result in important and interesting additional conclusions.

Further theoretical analysis on additional thermomodernization measures could focus on cooling loads during the summer period or possibility on utilizing renewable energy sources; however, this can be only addressed to the entire building community, not the individual owner, who has limited thermomodernization opportunities in such buildings, which was addressed in the article.

The presented approach is an important starting point for the revitalization and modernization of old tenements located in densely urbanized city centers, which have great potential in the area of reducing energy consumption and further economic analysis, as well as raising the standard of living of residents and countering energy poverty.

Author Contributions: Conceptualization, M.L.; methodology, M.L.; software, K.R. and M.L.; validation, M.L.; formal analysis, M.L. and K.R.; investigation, M.L.; resources, M.L. and K.R.; data curation, M.L.; writing—original draft preparation, M.L. and K.R.; writing—review and editing, M.L.; visualization, M.L. and K.R.; supervision, M.L.; project administration, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The work was partially accomplished under the project: "Mistrzowie Dydaktyki" umowa nr MNiSW/2020/114/DIR/WMT/W01—Operational Program Knowledge Education Development co-financed by the European Social Fund POWR.04.03.00-00-0074/17.

Conflicts of Interest: The authors declare no conflicts of interest.

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