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Predicting building energy utilization with the application of energy simulation software: Case study

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ABSTRACT

Maximizing energy efficiency of buildings is essential to meet the EU climate targets and strict national regulations. The way local climate influences energy performance of residential building and mitigation options was examined. A model of single-family house was analyzed in whole year energy simulation software WUFI Plus. Three Polish locations were investigated, namely Wrocław, Warszawa and Kołobrzeg. Implementation of the original meteorological dataset into WUFI Plus based on typical meteorological year (2005–2023) is a novel element of this work. Hourly heat and mass transfer, usable, final and primary energy indicators, and CO_2 emissions were calculated for a gas-boiler baseline and two alternatives: an air-to-water heat pump, and air-to-water heat pump with photovoltaic panels. The results for the gas-boiler scenario show location-dependent heating demand differences up to 30%; usable energy for heating ranged from 7561 to 9760 kWh/year, and EP of the system from 114 to 129 kWh/(m^2·year). Replacing the boiler with an air-to-water heat pump reduced final energy indicator by over 60% but produced similar CO_2 due to Poland's carbon-intensive electricity mix. Adding photovoltaic system, which covers electricity demand of only auxiliary equipment, cut CO_2 emissions by about 10%. These findings highlight the importance of climate-specific meteorological inputs and on-site renewables to meet the forthcoming energy performance standards.

Keywords: CO_2 emission, energy analysis, energy consumption prediction, simulation of energy, weather conditions.

INTRODUCTION

In the face of the intensifying climate crisis and rising energy costs, maximizing the energy efficiency of buildings has become a priority for modern construction in the European Union. This means that increasing emphasis is placed on constructing buildings with the lowest possible energy demand. The European Union (EU), as a major initiator of sustainable development efforts, has introduced increasingly strict regulations on the energy efficiency of buildings. The Directive of the European Parliament and of the Council (EU) 2024/1275 of 24th April 2024 on the energy performance of buildings (EPBD) [1] continues the regulations introduced in previous years aimed at reducing energy consumption in the building sector.

Climate neutrality in the building sector is associated with striving for zero emissions from buildings. This is an important direction because buildings in the EU account for 40% of final energy consumption and 36% of greenhouse gas emissions and indicate that 75% of buildings are energy-inefficient [1]. Moreover, about 80% of the energy used in EU houses is used for heating, cooling and hot water preparation [5,6] while the main energy sources for heating are still fossil fuels, such as natural gas (39%), oil (11%), and coal (3%) [1]. Buildings account for about 30% of global energy use and 26% of energy-related greenhouse gas emissions, which has prompted many countries since 2020 to accelerate efforts toward carbon neutrality [6]. The U.S. Energy Information Administration (EIA) predicts a further increase in building energy consumption of about 34% by 2050 under the baseline scenario [7].

In different EU countries, the transformation proceeds in varied ways, and EPBD recognizes this diversity by emphasizing that the actions to improve energy efficiency should consider local climatic conditions, adaptation to climate change, and the economic viability of investments. At the same time, it points out that the efforts to minimize energy consumption should not lead to a reduction in thermal comfort or indoor air quality in occupied buildings [8,9]. Thus, the 2024 EPBD amendment also emphasizes that Member States should establish appropriate indoor environmental quality standards.

Building energy performance is a key tool used to assess the energy quality of buildings and to support the implementation of energy efficiency policies. In Poland, the existing "sliding scale" certification system is being revised to align with the EU standards and enhance the transparency of energy assessments. The new classification will introduce energy classes from A+ to G, based on the non-renewable primary energy demand (EP). According to the Polish National Energy Conservation Agency (KAPE) proposal, the classes range from A for $0 < EP \leq 63$ kWh/(m²·year) to G for $EP > 531$ kWh/(m²·year), while the new ministerial regulation proposes a more stringent scale—from A+ for $EP \leq 0$, A for $0 < EP \leq 63$, to G for $EP > 150$ (presented values valid for October 2025). The revised framework will also include a second indicator, net energy supplied (ED), which accounts for on-site renewable electricity generation, and the new regulations are expected to come into force in June 2026.

Still, there is no information about the final shape of the regulations [14]; however, meeting such stringent requirements for buildings, both newly constructed and existing ones that will eventually be subject to these regulations, encourages the use of design tools for year-round energy simulations that account for local climate and enable analysis of indoor conditions. A range of simulation tools is available on the market, including annual energy and indoor climate simulations (e.g., WUFI Plus, EDSL TAS, EnergyPlus [15]), computational fluid dynamics (CFD)-based programs (ANSYS, FloVENT), system modelling (TRNSYS), and online platforms such as Green Building Studio. These software tools support the selection as well as evaluation of appropriate solutions and technologies in terms of energy efficiency.

Recent literature reflects the growing use of full-year dynamic simulations with advanced tools and real data. Libralato et al. [16] used WUFI Plus to perform 25-year (multi-year) hygrothermal simulations, finding that even slight climatic trends affect heating/cooling energy needs. The work emphasized that multi-year analysis (instead of a single typical year) provides a distribution of outcomes and can reveal moisture-related effects on comfort and demand. Likewise, Wąs [17] built a detailed WUFI Plus model of a passive house in Poland, driven by on-site measured climate (hourly temperature, humidity, solar radiation, wind) and including internal gains. Wąs showed that even a 4.7% difference in annual heating energy could arise simply from roof orientation (solar gains). Wang et al. [18] also demonstrated a coupled hygrothermal modeling: their study of reflective roof retrofit (in China) used WUFI Plus with recorded climate data, calibrated against three months of measured indoor temperature. The model included occupant schedules and natural ventilation (assumed 30 m³/h per person) to quantify cooling energy savings. López Gómez et al. [19] found that numerical weather prediction models, like the Global Forecast System, can serve as effective alternatives to traditional weather station data for building thermal simulations, often outperforming nearest weather station measurements. Segarra et al. [20] revealed substantial differences – up to 38% between annual and hourly time resolutions – when comparing on-site weather stations versus third-party weather data, identifying wind speed and outdoor temperature as the most influential parameters. Giama et al. [21] utilized the Weather Research and Forecasting model to predict future climate scenarios, projecting 20% heating load reduction and 60% cooling load increas by 2096–2100. Schroderus et al. [22] used WUFI 2D to simulate a 4-story hybrid log-concrete apartment building in Finland under historical and projected climates (RCP8.5). Using measured site weather and future CORDEX data, the authors found that current mold risk is very low but increases slightly under a 2080 high-emission scenario. The other case is from Portugal by Coelho et al. [23]. A high-thermal-mass church was modelled across multiple locations in Portugal. Using WUFI Plus with CORDEX downscaled weather, indoor temperature and humidity was mapped. Coastal locations had milder indoor climates than inland, and both temperature and humidity rise significantly under future RCP8.5 conditions. Fraunhofer Institute for Building Physics [24] developed new 2003–2010 "hygrothermal reference years" (including rain) for Germany. These were validated by comparing the WUFI-simulated moisture in wall components using both the new reference weather files and the actual multi-year measured climate. An example from Poland is a retrofit case of a tall building with capillary-active internal wall insulation simulated in WUFI Plus under varying indoor scenarios (ventilation rates, moisture loads). They showed how increased insulation thickness or higher ventilation alters moisture profiles in the masonry, and generated moisture-risk maps for different conditions [25].

In summary, the literature shows that whole-year dynamic simulation with WUFI Plus (or similar tool) is feasible and informative, especially when using location specific climate inputs [26,27] and realistic operational data [28]. Yet, no example that integrates multi-year local meteorological records for a Polish case was found. This justifies the adopted approach of customizing the WUFI Plus simulation to actual Polish climate data in order to improve the fidelity of energy use predictions.

In this article, the process of creating the model of a single-family building and the results of year-round energy simulations conducted in the WUFI Plus program were presented. The simulation results for three different building locations were analyzed. The original part of work is the implementation of actual meteorological data for these locations into the simulations. The impact of local climate on the energy performance of the residential buildings is especially important in the light of new regulation proposed. The model creation process, its limitations, and the method of defining boundary conditions in the program were described in detail. Year-round energy consumption, including heat and mass exchange, was simulated. The building energy consumption for different locations was compared, final and primary energy indicators were calculated, and the CO_2 emissions generated by the heating system were estimated. As the recent studies indicate, the importance of appropriate meteorological data use, this paper bridges the gap.

MATERIALS AND METHODS

Geometry

The building under consideration is a single-family house with a habitable attic; its net floor area is 145.42 m², and the gross building area is 188.41 m². The building has a gable roof with a slope of 40°. For the energy simulation, a three-dimensional geometric model of the building was created in SketchUp 2017. Its geometry is shown in Figure 1. To ensure the most realistic simulation results and to reproduce thermal relationships between spaces, the building was divided into 14 zones corresponding to the actual architectural subdivision of the building. On the ground floor, the zones include a living room with dining area, kitchen, study, bathroom, and utility room. On the upper floor, the zones include three bedrooms (one intended for two adults and two separate

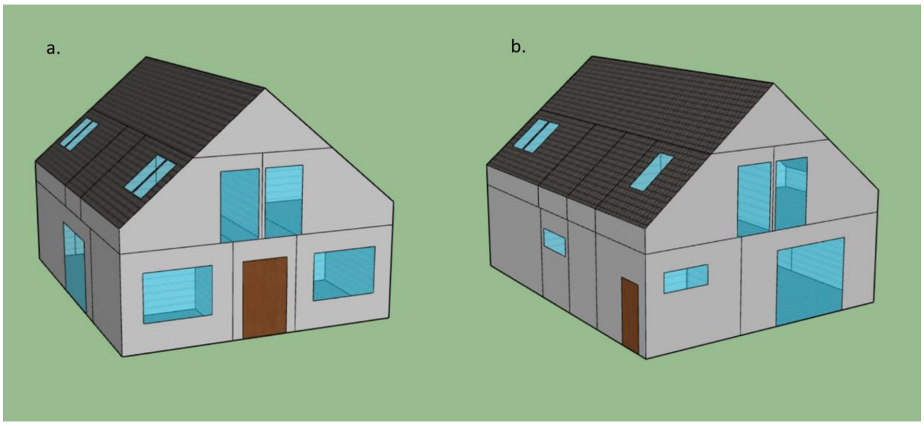

Figure 1. Three-dimensional visualization of the building created with SketchUp 2017: (a) view of the north-east elevation; (b) view of the south-west elevation

rooms for two children), a walk-in closet, a bathroom, and a laundry room.

Boundary conditions

In building energy simulation software, the so-called boundary conditions are of key importance. They are a set of assumptions and input data describing the environment and the building interactions with that environment, which must be specified for the simulation to be reliable. The boundary conditions can be divided into several groups: external conditions, internal conditions, construction and system.

Meteorological data

In WUFI Plus simulations, external boundary conditions describe the influence of meteorological parameters such as outdoor air temperature, outdoor relative humidity, and solar radiation intensity. These parameters depend on the geographic location of a building. Such data can be obtained from the weather files provided by research institutes or the internal climate database set within WUFI Plus. The origin location of the analyzed building was set as Wrocław – Biskupin district (51.1°N 17.11°E,). WUFI Plus program provides a built-in climate database only for selected Polish cities (Łódź, Warszawa, and Kołobrzeg); therefore, an individual climate dataset had to be implemented for the main location.

Following Polish guidelines, it is recommended to use meteorological data available on the Ministry's website [29] for building energy calculations. However, these data are based on IMGiW (Institute of Meteorology and Water Management) measurements from 1971–2000 [30], which no longer reflect current climatic conditions due to ongoing climate change. Moreover, this database was created based on the measurements recorded at Wrocław's airport meteorological station, which does not reflect urban climate specifics. In light of the above, for the simulation, a typical meteorological year (TMY) dataset, available from the EU Science Hub portal (2005–2023) was used. This satellite climate data records are available at Joint Research Centre (JRC) photovoltaic geographical information system [31,32].

The simulation included data of outdoor air temperature, outdoor relative humidity, global solar radiation in a horizontal plane and diffuse solar radiation in a horizontal plane. The data on precipitation for Wrocław location are not included in the database, so its impact on heat and mass exchange processes was not considered in the simulation. This is undoubtedly a certain limitation, as WUFI Plus is a hygrothermal simulation tool, but it is not disqualifying.

The hourly variability of the meteorological data and a view of the WUFI Plus working window are shown in Figure 2, while the monthly variability of the parameters is shown in Figure 3.

Construction of the building elements

In WUFI Plus, the construction of building elements is defined as a sequence of multiple layers arranged from the exterior to the interior, each

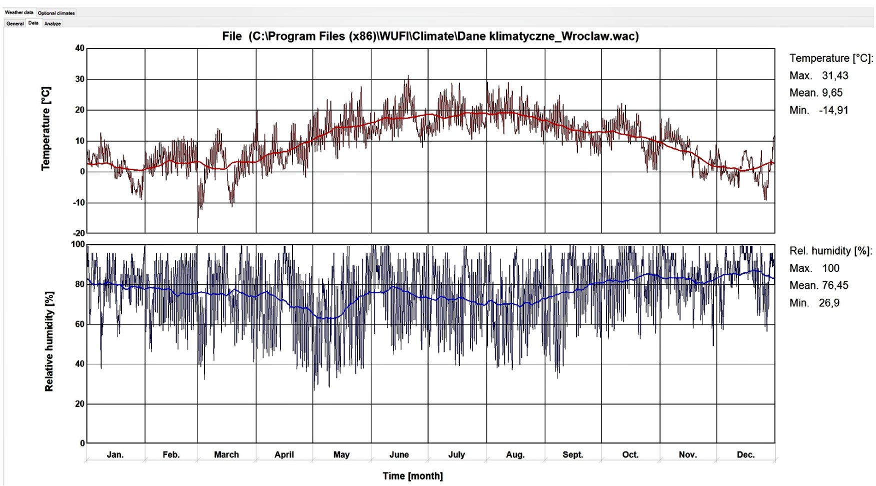

Figure 2. Workspace window of WUFI Plus program and selected meteorological data imported into the program for Wrocław: outdoor air temperature and outdoor air relative humidity

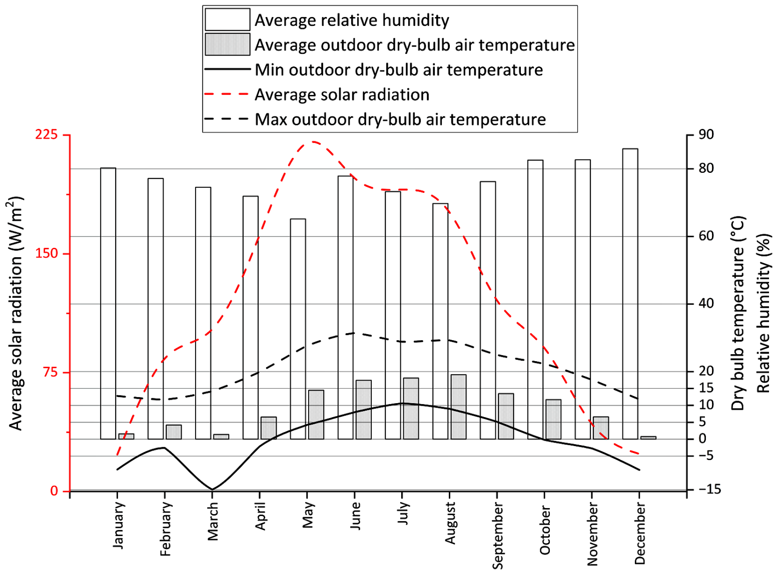

Figure 3. Average monthly values of outdoor air parameters for Wrocław

corresponding to a specific construction material defined by its physical properties (thickness, thermal conductivity, density, and specific heat). The construction of walls, floors and external envelope elements in analyzed building was based on the design documentation, and the material properties were taken from the WUFI Plus material database. All elements in the building met the thermal transmittance requirements (U_{max}) for the buildings constructed after 31st December 2020, according to Annex 2 of the Ministry of Infrastructure's Regulation of 12th April 2002 on technical conditions [33].

The building elements, their thermal transmittance values U [W/(m²·K)], and the maximum values defined in the Polish building regulations are summarized in Table 1.

Internal conditions

The building is intended for a four-person family consisting of two adults and two children. In each zone a user activity schedule was defined, distinguishing between weekdays and weekends. An example of sample window of internal heat gains based on periodic daily profiles is shown in Figure 4. Indoor temperatures and ventilation assumptions were defined in accordance with the Polish standard for calculating design heating loads [34].

Adjacent zones

The ground and the unheated attic were defined in the model as adjacent zones. For the ground, a sinusoidal function was created according to the literature guidelines [35], with an annual mean temperature of 10 °C and an annual amplitude of 5 K. It was assumed that the ground temperature peaked on 15th August 2024. The conditions of the unheated attic were similarly modelled as a sinusoidal function based on a research report [36]. The annual mean temperature of this zone was set at 16.5 °C with an annual amplitude of 7.5 K. The average relative humidity in the attic zone was set at 50%.

Heating system

The final step in preparing the simulation model was to define the heating system's operating parameters. The system covers transmission and ventilation heat losses. The heating season was assumed to last from 1st January to 1st May and from 1st September to 31st December. The heating load coverage for each room was set proportionally to its area. This simplification is due to the specifics of the WUFI Plus calculations – the precise distribution of heating coverage among rooms does not significantly affect the simulation results. Additionally, WUFI Plus assumes an ideal heating system. This means that the conditions within each zone are uniform (no vertical or horizontal temperature gradients, no thermal asymmetry) and the

Table 1. The structure of building elements, their heat transfer coefficients U [W/m^{2}K] and maximum permissible values

Type	Main construction components	U [W/(m²·K)]	U_{max} [W/(m²·K)]
External wall	20 cm thick aerated concrete blocks 20 cm polystyrene with a density of 30 kg/m^3	0.17	0.2
Internal wall	12 cm thick aerated concrete blocks	1.41	No requirements
Ground floor slab	20 cm polystyrene Finished with hardwood	0.18	0.3
Ceiling under the unheated attic	25 cm mineral wool	0.15	0.15
Roof	Ceramic roof tiles 25 cm thick mineral wool between and under the rafters	0.15	0.15
Intermediate floor slab	20 cm thick concrete layer 8 cm polystyrene with a density of 30 kg/m^3	0.4	No requirements
Window	Triple glazed	0.9	0.9
Roof window	Triple glazed	1.1	1.1
External door	-	1.27	1.3

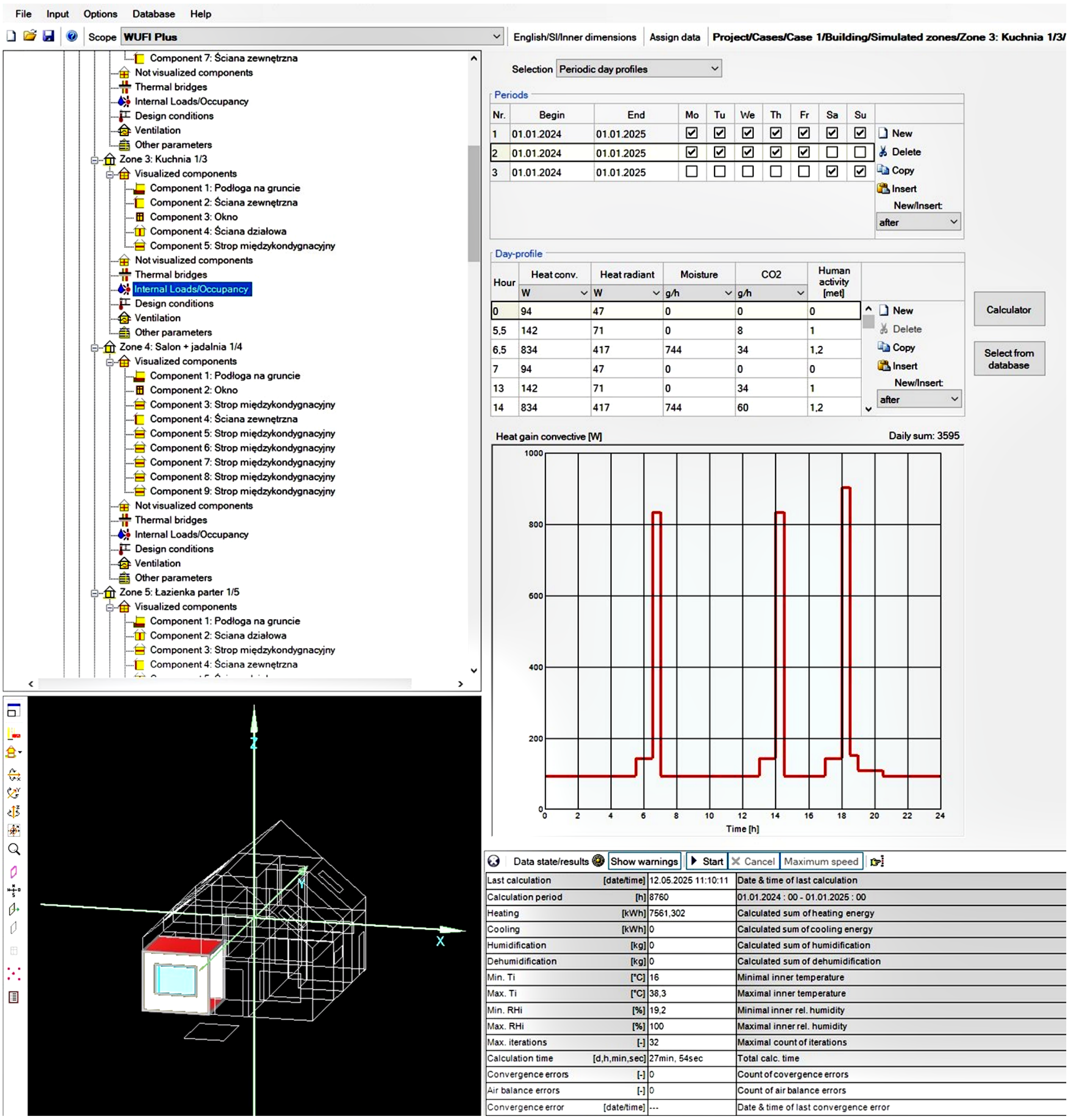

Figure 4. Workspace window – example internal heat gains for periodic daily profiles – kitchen

indoor temperature is the same at every point in the room. Thus, the model neglects real temperature stratification and assumes a uniform heat distribution within each space.

ANNUAL ENERGY DEMAND AND EMISSION CALCULATIONS

Heating and domestic hot water usable energy needs

Usable energy consumption for heating purposes was calculated by WUFI Plus. However, the energy consumption for domestic hot water (DHW) system needs to be calculated with application of other methods.

In the investigated case, the annual demand for usable energy for domestic hot water preparation ($Q_{u,W}$) was calculated based on Polish building regulations [37,38], in accordance with formula (1), following the assumption of a unit demand for domestic hot water of 1.4 dm³/(m²·day) [37]:

$$Q_{u,W} = V_{wi} \cdot A_f \cdot c_w \cdot \rho_w \cdot \cdot (\theta_w - \theta_o) \cdot k_R \cdot t_R / 3600 \quad (1)$$

where: $Q_{u,W}$ – annual usable energy demand for domestic hot water preparation [kWh/year], V_{wi} – unit demand for domestic hot water [dm³/(m²·day)], A_f – heated area [m²], c_w – specific heat of water – 4.19 [kJ/(kg·K)], p_w – water density – 1.0 [kg/dm³], θ_W – design temperature of domestic hot water (at the tap) – 55 [°C], θ_0 – design cold water temperature – 10 [°C], k_R– correction factor for interruptions in domestic hot water use (for a single-family home it is 0.90) [-], t_R – number of days in a year – 365 [day].

Total usable energy for the building is a sum of both: usable energy for heating and DHW systems.

To calculate the final energy of each system, one needs to define their total efficiencies. In the investigated study, a gas boiler was assumed as the heat source for both: space heating and DHW system. The efficiency of individual systems was determined based on seasonal averages of heat production, utilization and regulation, heat transfer, and heat storage, following [37]. For the heating system, this value was $\eta_H = 0.84$, and for domestic hot water, $\eta_w = 0.51$. Therefore, the final energy consumption was calculated as follows:

$$Q_{k,H} = \frac{Q_{u,H}}{\eta_H} \quad (2)$$

$$Q_{k,W} = \frac{Q_{u,W}}{\eta_W} \quad (3)$$

where: $Q_{u,H}$ – annual demand for usable energy supplied to the building for the heating system, [kWh/year], $Q_{u,W}$ – annual demand for usable energy supplied to the building for the domestic hot water system, [kWh/year], η_H – annual efficiency of heating system, η_W – annual efficiency of DHW system.

Building energy demand

The building's annual final energy demand (Q_k) was calculated using formula (4) [37]:

$$Q_k = Q_{k,H} + Q_{k,W} + E_{el.,aux} \quad (4)$$

where: Q_k – annual demand for final energy supplied to the building, [kWh/year], $Q_{k,H}$ – annual demand for final energy supplied to the building for the heating system, [kWh/year], $Q_{k,W}$ – annual demand for final energy supplied to the building for the domestic hot water system, [kWh/year], $E_{el,aux}$ – annual demand for final auxiliary energy supplied to the building for technical systems, [kWh/year].

The annual primary energy demand (Q_p) was calculated as follows:

$$Q_p = Q_{p,H} + Q_{p,W} \quad (5)$$

where: Q_p – annual demand for primary energy supplied to the building, [kWh/year], $Q_{p,H}$ – annual demand for primary energy supplied to the building for the heating system, [kWh/year], $Q_{p,W}$ – annual demand for final energy supplied to the building for the domestic hot water system, [kWh/year].

Primary energy demand for heating ($Q_{p,H}$) and for DHW preparation ($Q_{p,W}$) are calculated according to Formulas 6 and 7, respectively. In accordance with the regulation [37,38], non-renewable energy input factors of 1.1 and 2.5 were adopted for energy generation from natural gas and from the electricity grid, respectively.

$$Q_{p,H} = Q_{k,H} \cdot w_H + E_{el\,aux,H} \cdot w_{el} \quad (6)$$

$$Q_{p,W} = Q_{k,W} \cdot w_W + E_{el\,aux,W} \cdot w_{el} \quad (7)$$

where: w_H – non-renewable primary energy input factor for the heating system [-], w_w – non-renewable primary energy input factor for the domestic hot water system [-], w_e – non-renewable primary energy input factor for auxiliary electric energy [-], $E_{el,aux,H}$ – annual demand for final auxiliary energy supplied to the building for heating system, [kWh/year], $E_{el,aux,W}$ – annual demand for final auxiliary energy supplied to the building for the domestic hot water system, [kWh/year].

On the basis of the above, the indicators for annual usable energy demand (EU), final energy demand (EK) and annual primary energy demand (EP) are calculated as follows:

$$EU = Q_u / A_f \quad (8)$$

$$EK = Q_k / A_f \quad (9)$$

$$EP = Q_P / A_f \quad (10)$$

where: A_f – building floor area [m^2], EK – annual final energy demand indicator for building [kWh/(m$^2\cdot$year)], EP – annual primary energy demand indicator for building [kWh/(m$^2\cdot$year)].

CO_2 emissions

On the basis of the calculated annual energy demand and assuming the use of natural gas as the heat source for the building's central heating and domestic hot water, the system's CO_2 emissions were determined. In accordance with the guidelines of the regulation [37], the CO_2 emission equivalent per square meter (E_{CO2} in t_{CO2}/(m$^2\cdot$year)) of usable area is calculated using the formula:

$$E_{CO2} = \left(\begin{matrix} E_{H,CO2} + E_{W,CO2+} \\ +E_{aux,CO2} \end{matrix} \right) / A_f \quad (11)$$

where: $E_{H,CO2}$ – emission from the heating system, calculated according to formula (12) [t_{co2}/year], $E_{W,CO2}$ – emission from the heating system, calculated according to formula (13) [t_{CO2}/year], $E_{aux,CO2}$ – emission from the operation of auxiliary equipment, calculated according to formula (14) [t_{CO2}/year].

$$E_{H,CO2} = 36 \cdot 10^{-7} \cdot Q_{k,H} \cdot W_{CO2} \quad (12)$$

$$E_{W,CO2} = 36 \cdot 10^{-7} \cdot Q_{k,W} \cdot W_{CO2} \quad (13)$$

$$E_{aux,CO2} = 36 \cdot 10^{-7} \cdot \cdot \sum (E_{el,aux} \cdot W_{CO2,el,aux}) \quad (14)$$

where: W_{CO2} – CO_2 emission factor for natural gas – 57.65 [kg/GJ] [39], $W_{CO2,\,el,aux}$ – CO_2 emision factor for electric energy from grid – 597 [kg/MWh] (the unit was adjusted to the formula (13) – 165.8 [kg/GJ]) [40].

RESULTS AND DISCUSSION

In general, Poland belongs to the temperate climate zone. However, for engineering and design purposes in the heating season, it is divided into five internal climatic zones. A simulation of the building energy consumption was carried out for three selected locations representing three different zones: Wrocław (the reference location, south-western Poland, IInd zone; latitude 51.1°N, longitude 17.11°E), Warszawa (central-eastern Poland, IIIrd zone; 52.17°N, 20.97°E), and Kołobrzeg (seaside, north-western Poland, Ist zone; 54.17°N, 15.57°E), covering the whole year period from 1st January 2024 to 1st January 2025 with an hourly time step.

The amount of energy used for heating in the analyzed building at the reference location (Wrocław) was 7561 kWh/year, corresponding to a specific energy consumption of 40.1 kWh/(m$^2\cdot$year). In the building located in Warszawa, consumption was the highest and reached 130% of the reference value, with a specific energy consumption of 51.8 kWh/(m$^2\cdot$year). Kołobrzeg, despite being in the mildest climate zone, had a moderate result, namely 8043 kWh/year and 42.7 kWh/(m$^2\cdot$year), respectively – which corresponds to about 106% of the reference value. This may be due to the fact that Wrocław's location is more favorable in terms of solar gains during winter. The energy consumption for heating of the building for all locations analyzed by each building zone is presented in Figure 5, and the monthly breakdown is shown in Figure 6. The highest specific heat demand was found in the rooms with the largest area and glazing ratio, namely the living room on the ground floor (41.8 m^2), the upstairs bathroom (4.1 m^2), and the ground-floor

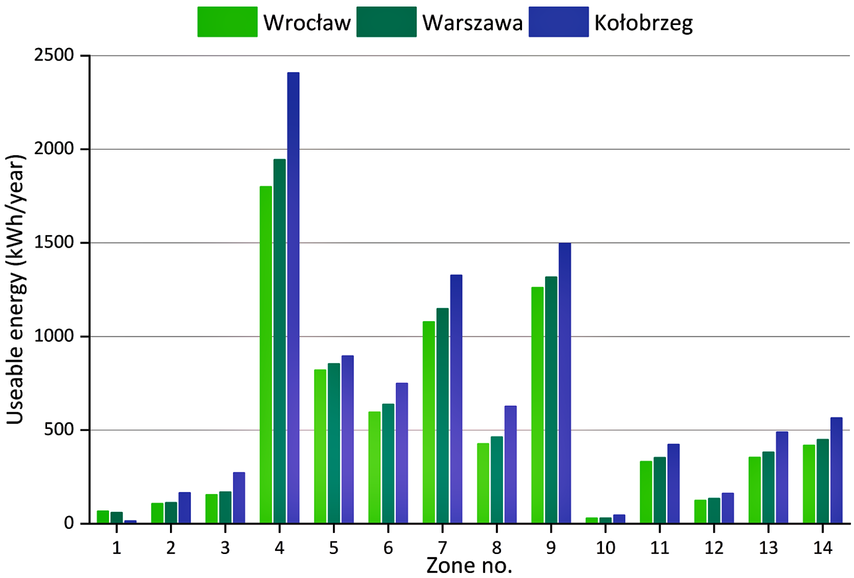

Figure 5. Usable energy demand for heating in each zone and the three chosen cities: zone 1 – vestibule, zone 2 – staircase (ground floor), zone 3 - kitchen, zone 4 – living room, zone 5 – bathroom (ground floor), zone 6 – technical room (heat source), zone 7 – cabinet, zone 8 – bedroom 1, zone 9 – bathroom (first floor), zone 10 – laundry, zone 11 – staircase (first floor), zone 12 – wardrobe, zone 13 - bedroom 2, zone 14 – bedroom 3

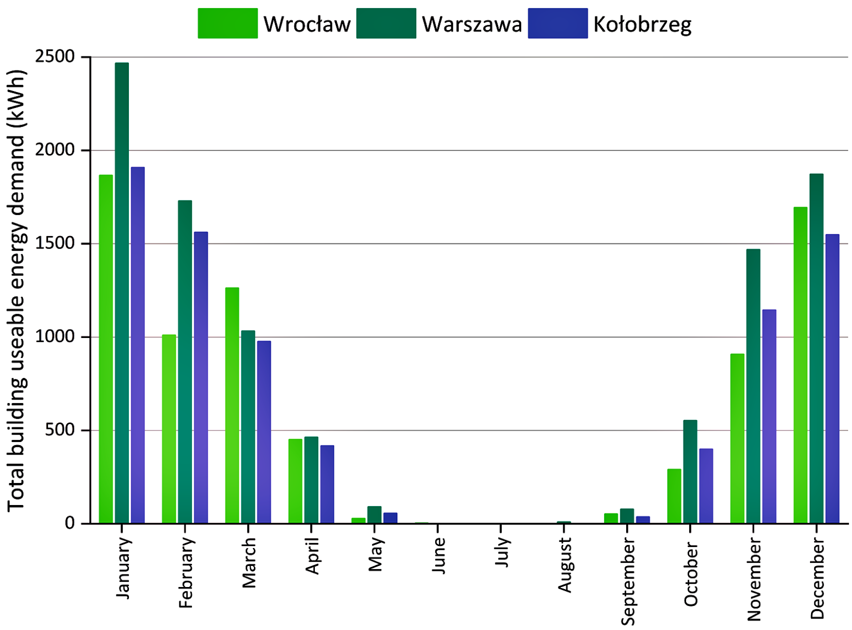

Figure 6. Monthly usable energy consumption for heating in the building for three locations

cabinet (14.2 m²). The lowest values were found in the utility rooms, the vestibule, and the upstairs laundry room.

The peak heat demand in the building occurs between November and February, according to the outdoor temperature profiles. The monthly demand in Wrocław and Kołobrzeg was comparable. However, the climatic conditions in Warszawa resulted in the highest energy demand, except in March (when Wrocław recorded the highest value) and in April (when the demand was similar in all three cities).

The annual energy demand of a building is influenced by solar radiation. Warszawa is the location with the lowest solar potential. Its average global radiation, following weather data, equals 111.5 W/m^2, while in Wrocław and Kołobrzeg this value reaches 119.7 and 121.3

W/m², respectively. The total annual heat gains through windows for each location amount to 7284, 7681 and 8865 kWh/year for Warszawa, Wrocław, and Kołobrzeg, respectively. However, the monthly solar heat gains of the building in summer do not exceed 1100 kWh in Wrocław, while in Warszawa (in June and July) they reach over 1200 kWh, and in Kołobrzeg almost 1400 kWh. These trends are consistent with the average solar radiation values defined in the meteorological databases used for selected locations. The lower solar gains in Wrocław may result from the specific nature of the building location – the very green area of the city: Biskupin district. Therefore, trees and shading of the building could have influenced the level of solar radiation.

However, during the heating season the influence of solar radiation on building energy demand is not particularly significant. In the winter months in Poland, when the heating demand is the highest, especially around the end of the calendar year, solar gains are the lowest and do not exceed 200 kWh per month. The monthly solar heat gains of the building in the selected locations are presented in Figure 7.

Despite the predefined heating season from 1st September to 1st May, each zone had a calculated number of heating days (referred in the software as a "heating period"), for which the heat losses and gains through individual building elements were calculated. The energy used by the building for heating purposes in all locations, along with other selected data, such as solar heat gains, heat losses through transparent and opaque partitions, and ventilation losses, are summarized in Table 2.

The calculation results were compared with the data presented in the study by Nowak [41], which presents the impact of the location of a building that meets the requirements specified in [33] on the consumption of usable energy for heating in relation to the reference value of 100% (Figure 8).

The lowest values were observed in buildings in the southwestern and western regions of Poland, with an increasing trend towards the northeastern parts, reaching up to 180% of the reference value. The simulation results are consistent with these trends.

In order to check whether the analyzed building meets the requirements of the building regulations [33] in terms of energy consumption and to determine the energy class of the building based on the proposed KAPE guidelines [10], further calculations were made. The energy used for domestic hot water preparation, calculated in accordance with actual regulations [37,38], was equal 5187 kWh/year in each analyzed city. The indicators of the annual demand for usable energy (EU), final energy (EK) and non-renewable primary energy (EP) were calculated in accordance with the current regulations [37].

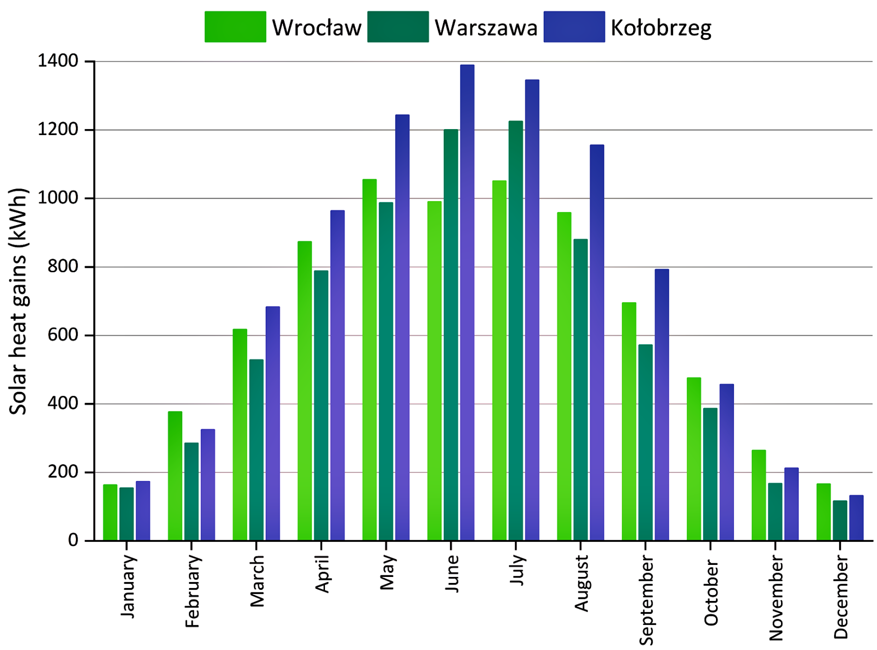

Figure 7. Monthly solar gains for the building located in three cities

Table 2. Energy calculations summary for three cities

Parameter	City		
	Wrocław	Warszawa	Kołobrzeg
Usable energy consumption for heating [kWh/year]	7561	9760	8043
Specific energy consumption for heating [kWh/(year·m²)]	40.1	51.8	42.7
Total solar gains during the heating period [kWh/year]	1175	1219	1233
Heat exchange through opaque partitions [kWh/year]	-1938	-2502	-2021
Heat loss through transparent partitions [kWh/year]	-2226	-2818	-2352
Ventilation heat loss [kWh/year]	-4487	-5732	-4846

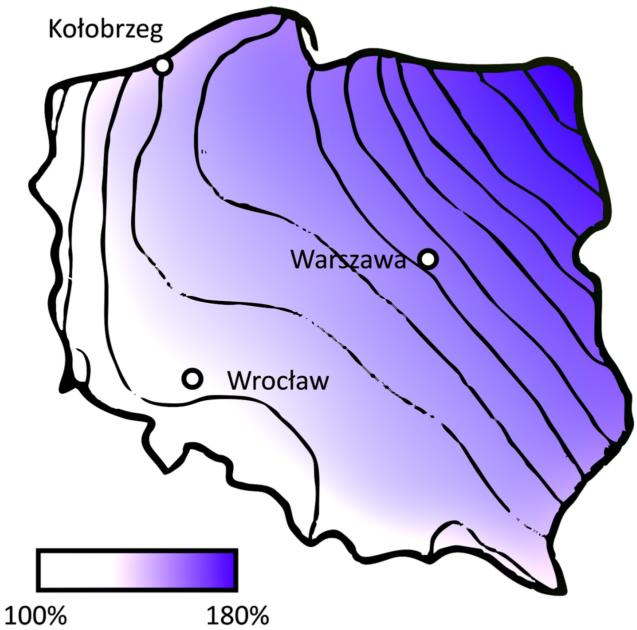

Figure 8. Diversification of the demand for usable energy for heating purposes for a building compliant with the requirements [33] (own study based on the literature [41])

The results of the annual energy demand are presented in Table 3. According to the KAPE classification [10], all locations qualify the building as class B. However, according to the more stringent, newly proposed (still as a draft) ministerial guidelines, the buildings fall into class E (113 < EP ≤ 131).

The achieved energy classes are not satisfactory; therefore, it would be desirable to undertake the actions to lower the energy indices by implementing the solutions based on renewable energy sources, e.g., by replacing the initially proposed heat source with the air-to-water heat pump. Modern heat pumps are highly efficient devices; however, according to the provisions of the Polish regulations [37], the total average seasonal efficiencies of the heating and DHW systems are only 2.54 and 1.33, respectively. The recalculated indicators of final and non-renewable primary energy are presented in a Table 4.

Changing the heat source resulted in a threefold decrease in the final energy demand for heating and a reduction by more than 2.6 for DHW. However, since the air-to-water heat pump used for heating requires additional auxiliary equipment, the $E_{el,aux,H}$ value is higher than in the less complex technical system based on a gas boiler. The heat pump itself also requires the electricity supply to operate. When it is supplied from the national power grid, its non-renewable primary energy factor equals 2.5 [38] and has a strong influence on the EP index. Although the EK indicator for all three locations decreased by more than 61%, the values of the EP coefficients dropped by only slightly over 17%.

This technical improvement does not change the building class according to the KAPE classification

Table 3. Energy demand and energy indicators calculated for all three locations

Parameter	City		
	Wrocław	Warszawa	Kołobrzeg
Q_u [kWh/year]	12 748	14 947	13 230
EU [kWh/(year·m²)]	67.7	79.3	70.2
$Q_{k,H}$ [kWh/year]	9001	11 619	9575
$Q_{k,W}$ [kWh/year]	8898		
$E_{el,aux,H}$ [kWh/year]	631		
$E_{el,aux,W}$ [kWh/year]	82		
$E_{el,aux}$ [kWh/year]	713		
Q_k [kWh/year]	18 612	21 230	19 186
$Q_{p,H}$ [kWh/year]	11 479	14 359	12 111
$Q_{p,W}$ [kWh/year]	9993		
Q_p [kWh/year]	21 472	24 352	22 104
EK [kWh/(m²·year)]	99	113	102
EP [kWh/(m²·year)]	114	129	117

Table 4. Energy indicators calculated for air-to-water heat pump for all three locations

Parameter	City		
	Wrocław	Warszawa	Kołobrzeg
$Q_{k,H}$ [kWh/year]	2977	3843	3167
$Q_{k,W}$ [kWh/year]	3412		
$E_{el,aux,H}$ [kWh/year]	688		
$E_{el,aux,W}$ [kWh/year]	13		
$E_{el,aux}$ [kWh/year]	701		
Q_k [kWh/year]	7090	7956	7280
$Q_{p,H}$ [kWh/year]	9163	11328	9638
$Q_{p,W}$ [kWh/year]	8563		
Q_p [kWh/year]	17726	19891	18201
EK [kWh/(m²·year)]	38	42	39
EP [kWh/(m²·year)]	94	106	97

[10]. However, according to the more stringent, newly proposed ministerial guidelines, the buildings are now classified at a higher level than initially, namely: for Wrocław location, the building achieves class C (75 < EP ≤ 94), and for Warszawa and Kołobrzeg – class D (94 < EP ≤ 113).

Further improvement would involve generating electricity for auxiliary equipment on-site from photovoltaic panels (PV). This would further lower the EP value by approximately 10% to 85, 96, and 87 kWh/(m²·year) for Wrocław, Warszawa and Kołobrzeg, respectively. To upgrade all three buildings to class C, additional on-site renewable energy generation would be required.

The calculated CO_2 emissions from the heating and DHW systems based on a gas boiler indicate the highest emissions in Warszawa (4.684 t_{CO_2}/year) and the lowest in Wrocław (4.140 t_{CO_2}/year). Changing the heat sources to an air-to-water heat pump does not result in a reduction of the equivalent of CO_2 emissions. This is due to the use of electricity from Polish national grid, which is generated mainly from hard coal. However, the on-site electricity production from PV panels may significantly reduce the local emission. The on-site electricity production from PV panels for the operation of auxiliary systems resulted in an almost 10% reduction in CO_2 emissions across

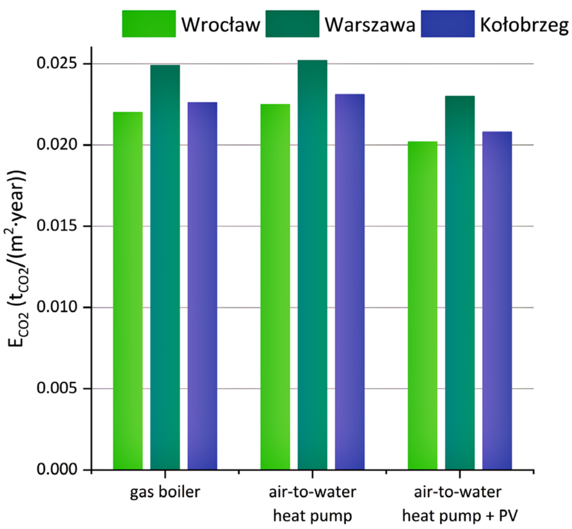

Figure 9. The CO_2 emissions related to the analyzed building location

Table 5. CO_2 emissions in a building located in three Polish cities for three different heat and energy sources

System	Gas boiler			Air-to-water heat pump			Air-to-water heat pump + PV		
Parameter	Wrocław	Warszawa	Kołobrzeg	Wrocław	Warszawa	Kołobrzeg	Wrocław	Warszawa	Kołobrzeg
$E_{H,CO2}$ [t_{CO2}/year]	1.868	2.411	1.987	1.777	2.294	1.890	1.777	2.294	1.890
$E_{W,CO2}$ [t_{CO2}/year]	1.847			2.037			2.037		
$E_{aux,CO2}$ [t_{CO2}/year]	0.426			0.418			0		
Sum	4.140	4.684	4.260	4.233	4.750	4.346	3.814	4.331	3.928

all three locations. Additional reductions may be achieved by applying a larger number of PV panels connected to energy storage batteries, or by using a brine-to-water heat pump with a more temperature-stable and efficient ground heat source. The results of emission calculations for individual systems and all three locations are presented in Table 5, while the CO_2 emissions per building area, with the division on specific systems, are shown in Figure 9.

CONCLUSIONS

The study demonstrated the importance of using whole-year energy simulation software for predicting energy consumption of a building.

Simulation tools, such as WUFI Plus, allow for detailed, hour-by-hour analyses of buildings, taking into account local climate conditions. However, not all typical meteorological year (TMY) databases include precipitation data. Since WUFI Plus is a hygrothermal simulation tool, neglecting precipitation may affect the final results. It is therefore advisable, whenever possible, to use a database supplemented with precipitation data when working with software that models heat and mass transfer processes.

WUFI Plus is a powerful tool, however, to maintain a balance between the technical parameters of the equipment, computational time, and accuracy, it is necessary to apply certain simplifications, such as assuming an ideal heating system and uniform heat distribution in each space. A detailed analysis of the air parameter distribution within a room, however, can be performed using other software, such as FloVENT or ANSYS (CFD tools). In the future, the outcomes from WUFI Plus may be used not only for estimating the building energy class, but also as boundary conditions for CFD simulations aimed at modeling indoor thermal comfort environment in chosen external conditions.

Following the calculation outcomes of two alternative systems based on heat pumps as heat sources, it is also worth considering in future work how, and to what extent, the seasonal average efficiencies of technical systems defined in Polish regulations relate to real values.

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