Original Paper

Indoor and Built Environment

Indoor and Built Environment
0(0) 1–16

DOI: 10.1177/1420326X16631031
ibe.sagepub.com
SAGE

Energy performance of buildings in Poland on the basis of different climatic data

Magdalena Grudzińska[1] and Ewa Jakusik[2]

Abstract

Typical Meteorological Years (TMY) were prepared in Poland due to the introduction of obligatory energy certification for buildings. They are based on source data collected by the Institute of Meteorology and Water Management from 1971 to 2000. Predictions indicate that until the end of the 21st century, the air temperature will increase. Therefore, the characteristics obtained with the use of TMY may differ from the energy demand of buildings used nowadays. This article compares energy demand calculated with the use of TMY and subsequent climatic data from 2001 to 2012, for three different locations in Poland. The analyses were performed with the use of the dynamic simulation computer program, for typical living quarters in a multifamily residential building with different construction and window orientation. Results obtained with the use of TMY and subsequent climatic data show that the typical years can be used for the evaluation of heating demand. However, cooling demand calculated with the use of TMY was significantly lower in comparison with the mean cooling demand for the years 2001–2012. This may distort the energy needs and indoor environment conditions in summer, and cause discomfort or unnecessary energy use in presently occupied dwellings.

Keywords

Energy demand in buildings, Typical Metrological Year, Climatic data, Computer simulations, Overheating risk

Accepted: 15 January 2016

Introduction

Demand for energy used to heat or cool down buildings depends mainly on two groups of factors: outdoor climate and the thermal quality of the building envelope. The thermoinsulating power of building partitions can be consciously selected by the designer, and in normal conditions of use undergoes only slight changes, e.g. due to the ageing of insulating materials and their increased moistness. The external environment, on the other hand, is subject to constant changes connected with the daily and annual cycles of variations in temperature, air humidity, insolation, wind activity, etc. To establish a reliable manner of assessing the energy performance of buildings, standardised sets of climatic data, corresponding to multiannual outdoor conditions, are applied. These data can take different forms, depending on the adopted method of calculating energy demand.

The degree-days method was the first one which allowed energy demand to be linked to the conditions of the external environment. Calculations require a minimum range of climatic data, which are relatively easy to obtain, i.e. average daily temperatures of outside air.[1] Later, stationary and quasi-stationary methods use a broader range of climatic data, such as air temperature and solar radiation intensity, in the form

[1]Faculty of Civil Engineering and Architecture, Lublin University of Technology, Lublin, Poland
[2]Institute of Meteorology and Water Management – National Research Institute, Center for Poland's Climate Monitoring, Warsaw, Poland

Corresponding author:
Magdalena Grudzińska, Faculty of Civil Engineering and Architecture, Lublin University of Technology,
st. Nadbystrzycka 40, 20-618 Lublin, Poland.
Email: m.grudzinska@pollub.pl

of long-term averaged monthly or annual parameters.[2,3] Dynamic simulations, in which thermal balance concerns short time steps (usually not exceeding 1 h) and directly takes into consideration heat accumulated and released from the mass of the building, are regarded as the most accurate for determining energy demand.[4] These methods, on account of the high degree of their complexity, basically serve for the purposes of computer calculations and require a very broad range of data describing the outdoor environment. In the majority of computer programmes, the data indispensable for carrying out a simulation include outside air temperature, air humidity, atmospheric pressure, direction and velocity of wind, and intensity of direct and diffuse solar radiation.[5] These parameters must be known for each hour of the period for which calculations are made.

Considering the significant costs and great labour intensity of preparing this kind of data, the so-called Typical Meteorological Year (TMY) is introduced, replacing long-term measurement data with a representative period of one year.[6,7] It contains 8760 hourly records illustrating the course of required climatic parameters.

TMY collection methods are different in different countries.[8–11] They may be based on statistical analysis leading to the creation of a 'fictional' year composed of selected real months, or they may specify the criteria of a selection of a real year used for analysing heating and cooling demand. Statistical methods are considered most effective for mapping average multiannual climatic conditions.[6,7,12,13] The literature on the subject indicates that simulations of a building's energy performance by means of TMY created with the use of Finkelstein–Schafer statistics allow energy demand to be calculated with a margin of error not exceeding 5% in comparison with simulations conducted for multiannual climatic data.[7,8]

TMYs were prepared in Poland in 2004 due to the introduction of obligatory energy certification for buildings. The TMY creation was based on source data collected by the IMWM-NRI (Institute of Meteorology and Water Management – National Research Institute) in 61 weather stations from 1971 to 2000. The compilation procedure using Finkelstein–Schafer statistics was adopted in accordance with the standard EN ISO 15927-4,[14] coherent with the EN ISO 13790.[3] The most representative months were the ones in which the average values of the variables, their frequency distribution and correlations were closest to the long-term averages. The key parameters for energy calculations were dry-bulb temperature, solar radiation on a horizontal surface and relative humidity. Information on TMY is available on the website of the Ministry of Infrastructure and Development (http://www.mir.gov.pl). The data comprise the following parameters: sequential number of a given hour of a year, month, day and Coordinated Universal Time (UTC) hour, dry-bulb temperature (°C), relative humidity (%), moisture content (g/kg), wind velocity (m/s), wind direction in 36 sectors (according to the key), total solar radiation on a horizontal surface (W/m^2), direct and diffuse solar radiation on horizontal and inclined surfaces (W/m^2), sky radiation temperature (°C).

Predictions indicate that starting from the 1990s until the end of the 21st century, the global warming effect and the average outside temperature will increase.[15,16] Milder winters and warmer summers may result both in a lower demand for heating and in the wider use of cooling systems in residential buildings.[17,18] Recently, extensive research on the subject was conducted in the United Kingdom, paying special attention to the possibility of overheating the existing building stock.[19–21]

These findings led the authors to examine, how the mandatory procedures in Poland provide for a reliable analysis of typical residential buildings constructed and inhabited after the year 2000. Therefore, the energy demand calculated with the use of measurement data collected from 2001 to 2012 was compared with the energy demand obtained with the use of freely available TMY, representing the preceding three decades. The analyses were carried out for both heating and cooling seasons.

Climatic data assumed in calculations

Poland lies in a zone of moderate climate of a transitory character, between a marine climate in the West and a continental climate in the East. In the winter, the isotherm system resembles a longitudinal one, and the temperature increases in the western direction. In the summer, the isotherm system resembles a latitudinal one, with the highest values in the central part of the country. In the 1970s, five climatic zones were distinguished in Poland in the winter period and two in the summer period, represented by differentiated design temperatures of external air (Figure 1). These temperatures are taken for the sake of the power adjustment of heating systems.[22] In the presented analyses, three localities were chosen – Łeba, Wieluń and Włodawa, belonging, respectively, to the first-, second- and third-climatic zones (Table 1). These zones cover over 75% of the Poland's area.

The meteorological station in Łeba is situated in the middle part of the Slovincian Coast, at a distance of approximately 700 m from the shore of the Baltic Sea and about 2.5 km from the mouth of the Łeba River. The meteorological garden lies between meadows and a boggy area of the Łebsko lake floodlands, the Łeba River and a strip of a dense forest. Wieluń is a town in the south-eastern part of the Łódź province within

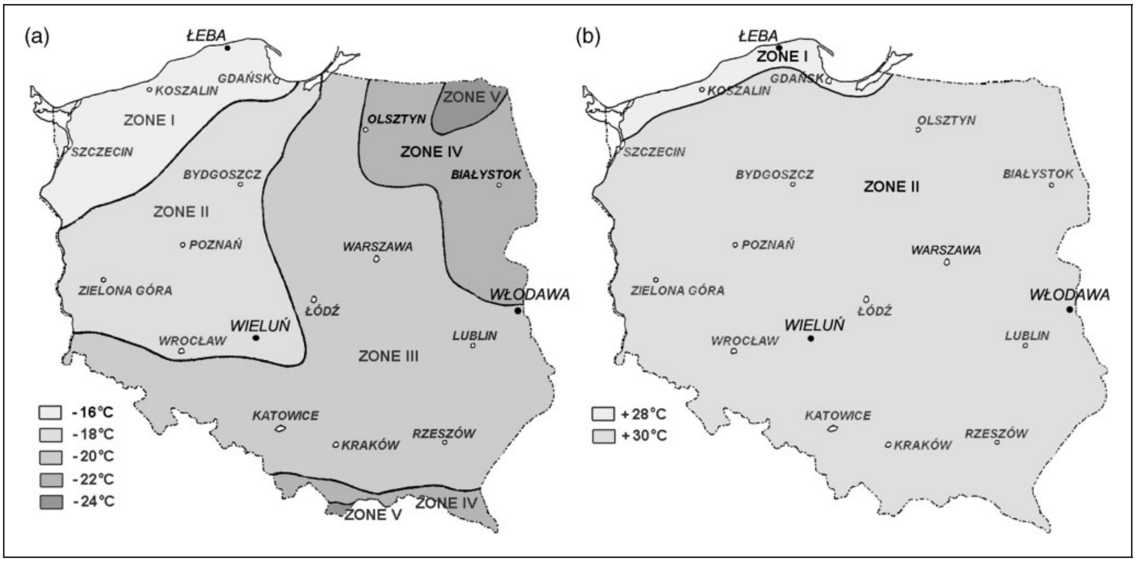

Figure 1. Climatic zones in Poland and the design temperatures: (a) during winter and (b) during summer, according to the standard PN – 74/B – 02403.[22]

Table 1. Location of the meteorological stations.

No.	Station	Climatic zone	Latitude (E)	Longitude (N)	Altitude (m. asl)	Type of measurements
1.	Łeba	I	54°45′	17°32′	2	Standard + actinometric
2.	Wieluń	II	51°12′	18°33′	199	Standard + actinometric
3.	Włodawa	III	51°33′	23°32′	177	Standard + actinometric

the Wieluń Upland, being part of the Kraków-Czestochowa Upland. A regional measurement and observation station in Wieluń lies in the southern part of the town on its highest rise. Włodawa is situated in the eastern part of the Lublin Region, on the left bank of the Bug River, close to the mouth of the Włodawka River. The hydrological and meteorological station lies in the north-western extreme of the town, in open space which, after about 1 km, turns into high-density urban housing.

Measuring instruments

The meteorological data used in the present study come from the weather stations and meteorological posts of the IMWM-NRI, the same source that was used for the creation of TMY. All the data underwent a control and verification process before they were inserted in the Institute's central database. The measurements and observations were conducted in compliance with the requirements and recommendations of the World Meteorological Organization (WMO). A meteorological garden was the main place of measurements within the measurement and observation station. In the central place of a meteorological garden, there was a Stevenson screen, which contains the following equipment: automatic sensors measuring air temperature and humidity, mercurial thermometers: wet and dry bulb ones (forming a psychrometer), and a maximum-minimum thermometer (Table 2).

The Stevenson screen would provide homogeneous conditions of measuring temperature and air moisture at a height of 2 m above ground level. Apart from the standard programme (i.e. carrying out round-the-clock measurements of air temperature and humidity, atmospheric precipitation, wind velocity and direction), an extended measurement programme embracing actinometric measurements was run at selected stations of the IMWM-NRI. Two sensors produced by Kipp & Zonen, measuring the solar spectrum from 300 to 3000 nm and recording the data every minute, were used for measuring solar radiation. The first of the sensors, a pyranometer (Table 3), was used for measuring diffuse solar radiation that reached the horizontal surface from any point of the sky, except for radiation coming from the direction of the Sun.

This was achieved because of the installed diaphragm, which provided the shading for the dome of

Table 2. World Meteorological Organization requirements concerning glass thermometers (°C).

No.	Type of thermometer	Ordinary	Maximum	Minimum
1.	Temperature range	−39 to +45	−30 to +50	−40 to +40
2.	Calibration range	−30 to +40	−25 to +40	−30 to +30
3.	Maximum error	<0.2	±0.2	±0.3
4.	Maximum difference between maximum and minimum correction within the range	0.2	0.3	0.5
5.	Maximum variation of correction within any interval of 10°C	0.1	0.1	0.2

Table 3. Characteristics of the pyranometers used at IMWM-NRI stations.

No.	Name, type and producer	Pyranometer CM6B, Kipp & Zonen, Netherlands, I class (64 thermocouples)
1.	Spectral range	310–2800 nm (50% points)
2.	Sensitivity	9–15 μV/Wm^{-2}
3.	Impedance	70–100 Ω
4.	Response time	<18 s (95%)
5.	Nonlinearity	<1.2% (<1000 W/m^2)
6.	Operating temperature	−40°C to +80°C
7.	Temperature dependence of sensitivity	±2% (−10°C to +40°C)
8.	Irradiance	0–1400 W/m^2 (max. 2000 W/m^2)
9.	Tilt error	±1% (beam 1000 W/m^2)

the sensor. The second of the sensors, a pyrheliometer, measured the direct beam solar irradiance, i.e. radiation falling on the surface, which is perpendicular to the direction of the Sun.

Characteristics of climatic conditions in the multiannual period of 2001–2012

The comparative period adopted in the research comprises the years from 2001 to 2012, which follows the time period used for creating TMY. Source data used in simulations included the following observed and measured parameters: the code of the station, year, month, day, UTC hour, dry-bulb temperature, relative air humidity, wind velocity and wind direction, as well as values of total and diffuse solar radiation on a horizontal surface. Solar radiation data were registered every hour, and the other data every 3 h. Data recorded 8 times a day were connected using linear interpolation to determine hourly values. The main measurement results comprising air temperature and solar irradiation for Łeba, Wieluń and Włodawa were collected in Tables 4 and 5, and compared with the values included in TMYs. The heating season was assumed to last roughly from October till May, and the cooling season encompass June, July, August and September. The real lengths of the heating and cooling seasons may differ depending on the building construction and thermoinsulating power of external partitions, but a uniform division of the year allows climatic data to be more clearly compared.

Łeba lies in the zone of a warm, transitory, moderate climate with the influences of a maritime and continental climate. The maritime climate prevails over the continental one, due to mild winters with frequent thaws, a small number of days with snow cover, a small number of days with extreme temperatures, high air humidity, a considerable number of days with precipitation and, finally, more rainfall in the autumn than in the spring.[23] In the period of 2001–2012, the average temperature in the heating season was the median value, while in the cooling season, this would be the lowest temperature from among the presented localities. The average annual air temperature was 8.3°C, while the warmest month of the year was July (the average temperature was 17.9°C). The absolute maximum temperature in Łeba during the analysed 12 years was 32.8°C, which was recorded on 12 July 2010. The coldest month was January (with an average temperature of −0.2°C), while the absolute minimum temperature in the period of 2001–2012, was −24.7°C, and this was recorded on 6 February 2012. The sum of insolation on the horizontal surface was among the lowest ones from the chosen locations. The share of direct solar radiation in the heating and cooling seasons was 54.1% and 59.7%, respectively.

Wieluń, according to the division into climatic regions,[24] lies in the transitory zone between the climate of the Land of Great Valleys and the Mid-Polish Uplands. Maritime polar air masses clash there with typically continental polar ones, which leads to great climatic changeability both in the daily and the annual course of air temperature. The region of Wieluń is

Table 4. Average dry bulb temperatures (°C) from 2001 to 2012 and according to TMY.

No.	Locality	Period	Heating season	Cooling season	Annual average	Minimum temperature	Maximum temperature
1.	Łeba	2001–2012	4.4	16.1	8.3	−24.7 (06 February 2012, 6.00 a.m.)	32.8 (12 July 2010, 12.00 a.m.)
		TMY	4.0	15.6	7.9	−13.8	31.3
2.	Wieluń	2001–2012	4.7	17.5	9.0	−26.0 (23 January 2006, 6.00 a.m.)	35.9 (29 July 2005, 12.00 a.m.)
		TMY	4.3	16.7	8.4	−16.2	34.3
3.	Włodawa	2001–2012	3.8	17.3	8.3	−29.5 (24 January 2006, 3.00 a.m.)	35.2 (06 August 2012, 12.00 a.m.)
		TMY	3.2	16.3	7.6	−22.1	30.9

TMY: Typical Meteorological Years.

Table 5. Solar irradiation on a horizontal plane (kWh/m^2) from 2001 to 2012 and according to TMY.

No.	Locality	Period	Heating season	Cooling season	Annual sum	Maximum hourly insolation
1.	Łeba	2001–2012	485.25	543.40	1028.65	0.93 (06 June 2009, 12.00 a.m.)
		TMY	396.96	450.43	847.39	0.91
2.	Wieluń	2001–2012	557.76	587.08	1144.84	0.99 (10 June 2005, 1.00 p.m.)
		TMY	471.68	479.28	950.96	0.98
3.	Włodawa	2001–2012	550.41	602.48	1152.89	0.99 (06 July 2006, 1.00 p.m.)
		TMY	458.64	501.29	959.93	0.99

TMY: Typical Meteorological Years.

characterised by warm, long summers and moderate winters. In the period of 2001–2012, the highest temperatures in the heating and cooling seasons, as well as the highest annual mean air temperature (9.0°C) were recorded here. January was the coldest month (with an average temperature of −1.4°C), while July was the warmest one (with an average temperature of 19.7°C). In the period of 2001–2012, the warmest day was 29 July 2005, with a temperature of 35.9°C, while the coldest one was 23 January 2006 with a temperature of −26.0°C. In the heating season the greatest sums of solar radiation were measured here, and insolation in the cooling season was also quite high. In the heating and cooling seasons direct solar radiation constituted, respectively, 58.4% and 52.9% of total solar radiation reaching the horizontal surface.

The climatic conditions of the area of Włodawa are shaped by various masses of air. Usually these are maritime polar air masses, less frequently continental polar and arctic ones, while the rarest come from tropical air. The area is distinguished by a longer summer, lasting up to 98 days, as well as a longer winter than in central Poland (up to 80 days). The insolation slightly exceeds the Polish average and usually amounts to 4.6 h. The warmest month in the period of 2001–2012 was July (with an average temperature of 20.0°C), while the coldest one was January (−2.9°C). The absolute maximum temperature in Włodawa, amounting to 35.2°C, was recorded on 6 August 2012, whereas the absolute minimum temperature of −29.5°C was recorded on 24 January 2006. The conditions connected with solar radiation in this region are very favourable. The annual sum of solar radiation on the horizontal surface and the sum of solar radiation in the cooling season were the highest from among the presented locations. The insolation in the heating season was also quite high. Direct solar radiation constituted over 58% of total solar radiation in the winter and about 50% in the summer.

For all the locations the multiannual average temperatures of the heating season, the cooling season and the whole year were slightly higher than the average temperatures determined on the basis of TMY (Figures 2 and 3, Tables 4 and 5). Nevertheless, these differences are not statistically important (with the exception of Włodawa). The average sums of solar radiation on the horizontal surface coming from the period of 2001–2012 were, however, statistically higher for

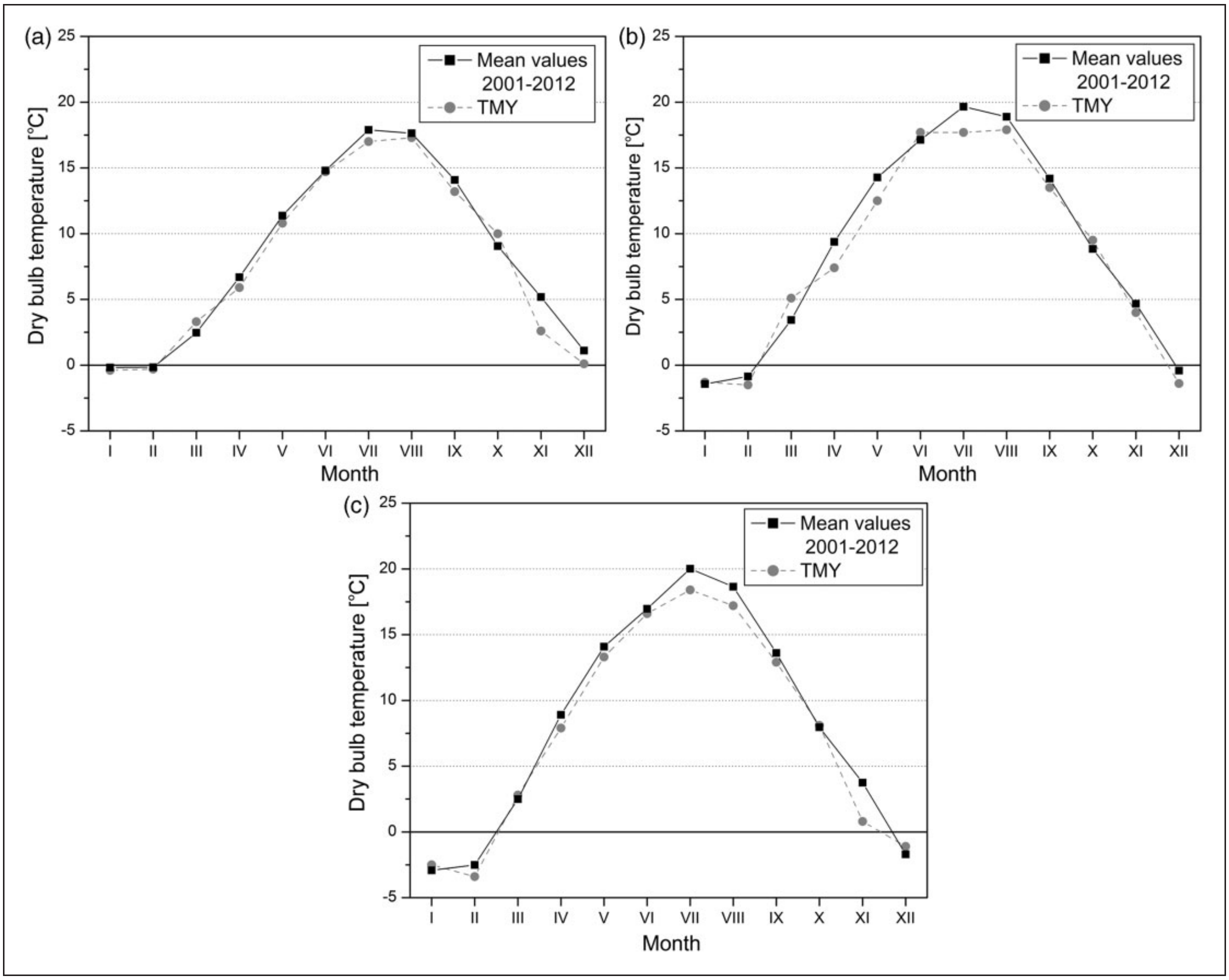

Figure 2. Dry bulb temperatures: (a) Łeba, (b) Wieluń and (c) Włodawa.

each location than the values given by the TMY (usually by slightly more than 20%). The share of direct solar radiation was significantly smaller in the TMY than in real data, and equalled on average 25.2%, 31.7% and 32.9% for Łeba, Wieluń and Włodawa, respectively.

Methodology of energy demand calculations

Calculations of energy needs were made using the BSim simulation program. It enables the dynamic analysis of energy demand in living quarters and public utility facilities. Calculations are based on the control volume method, in which structural elements of a building and closed air zones are represented by nodal points with defined physical parameters such as density, conductivity and heat capacity. For each air zone, a separate balance equation was created, including heat flux flowing through the control surface, transmission of solar radiation through transparent elements, heat flux generated by installation systems and transported through ventilation, and infiltration or air exchange between the exterior and the interior of a building. Continuous time processes of heat transfer were modelled by division into discrete time steps having a finite length of 1 h or less.[25]

The analysed apartment had a floor area of approximately 74 m^2 and a net height amounting to 2.7 m. The flat was located in the middle section of the building's storey, and it had two opposite external walls with the thermal transmittance coefficient equal to 0.30 W/m^2K. In each exterior wall, there were two 1.5 m × 1.5 m windows, chosen due to the requirements concerning the delivery of minimum daylight (Figure 4).

The thermal transmittance coefficient of the windows was 1.7 W/m^2K. These values fulfil the obligatory requirements in Poland for new buildings designed from 2002 to 2013. The remaining partitions adjoined same type of heated rooms and were treated as adiabatic

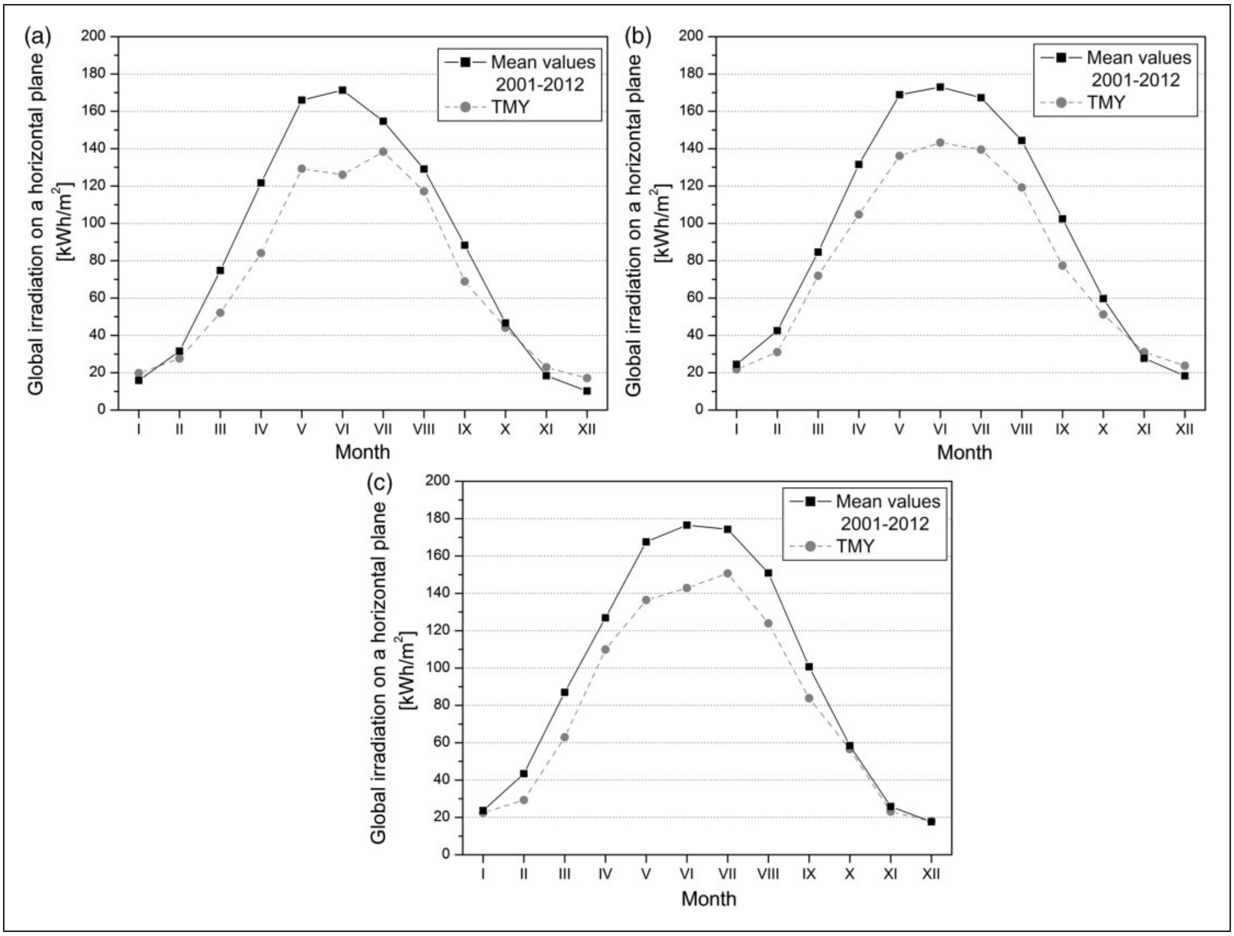

Figure 3. Solar irradiation on a horizontal plane: (a) Łeba, (b) Wieluń and (c) Włodawa.

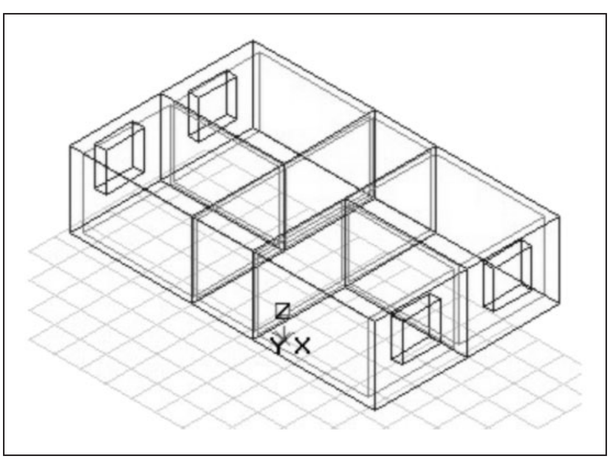

Figure 4. The outline of the flat simulated in the BSim program.

surfaces. Interior gains with the value of 4.5 W/m^2 and a ventilation of 0.5 ach were implemented. According to national data, these are typical parameters of traditional residential buildings.[3,26] The ventilation rate was presumed constant during the day and night. Wind-driven infiltration was not included in the analyses, because the gaps in climatic data concerning wind speed and direction were too wide to model the air flow correctly. More intensive night time ventilation could diminish the overheating of rooms, but as the research did not concentrate on strategies of reducing the energy need, these issues were not taken into account.

The radiators were controlled on the basis of operative temperature of the selected zone. Set point temperature of the heating system was 20°C, and the power control curve was defined as a continuous polyline consisting of three straight parts. The maximum power (100 W/m^2) was available when the outdoor temperature reached −20°C, and the minimum of the required power (amounting to 80 W/m^2) was available when the outdoor temperature was 10°C. At temperature in between the available power varied linearly. The heating system was working within the time schedule comprising the months from September to May.

Concerning the cooling system, this was simulated as a thermostat-controlled cooling radiator, e.g. a cooling ceiling or other cooling surface placed in the current thermal zone. The system turned on when the internal operative

Table 6. Selected simulation results – Heating demand.

No.	Location	Building construction	Window orientation	TMY (kWh/year)	Period 2001–2012 Mean (kWh/year)	Min/max (kWh/year)	Standard deviation (kWh/year)	Variation coefficient (%)	Reduction in demand for heating compared with TMY (%)
1.	Łeba	Massive	N–S	**2616.6**	**2338.4**	1986.1/2897.4	238.9	10.2	10.6
2.			E–W	**2733.0**	**2493.7**	2086.1/3058.6	243.8	8.9	8.8
2.		Lightweight	N–S	**2666.0**	**2390.4**	2040.5/2964.7	241.8	9.0	10.3
4.			E–W	**2777.5**	**2528.5**	2123.3/3122.3	250.5	9.9	9.0
5.	Wieluń	Massive	N–S	**2353.7**	**2191.0**	1742.2/2618.6	227.4	10.4	6.9*
6.			E–W	**2451.1**	**2416.3**	1966.6/2857.6	233.2	9.7	1.4*
7.		Lightweight	N–S	**2418.8**	**2273.8**	1837.8/2744.2	228.4	10.0	6.0*
8.			E–W	**2515.2**	**2471.8**	2037.1/2943.9	233.0	9.4	1.7*
9.	Włodawa	Massive	N–S	**2759.4**	**2556.8**	2070.1/2829.1	225.7	8.8	7.3
10.			E–W	**2850.4**	**2737.7**	2282.5/3038.4	228.4	8.3	4.0*
11.		Lightweight	N–S	**2819.8**	**2630.3**	2171.5/2900.1	213.1	8.1	6.7
12.			E–W	**2908.8**	**2788.5**	2361.6/3086.9	220.4	7.9	4.1*

TMY: Typical Meteorological Years. *averages from multiannual period are not statistically smaller than results obtained on the basis of TMY (t-test for one average, confidence level 0.95).
Note: Bold faces are basic compared values.

Table 7. Selected simulation results – Cooling demand.

No.	Location	Building construction	Window orientation	TMY (kWh/year)	Period 2001–2012 Mean (kWh/year)	Min/max (kWh/year)	Standard deviation (kWh/year)	Variation coefficient (%)	Increase in demand for cooling compared with TMY (%)
1.	Łeba	Massive	N–S	**−169.71**	**−244.8**	−385.7/−122.3	87.3	35.7	44.2
2.			E–W	**−233.1**	**−520.7**	−679.7/−264.1	131.1	25.2	123.4
3.		Lightweight	N–S	**−252.4**	**−319.1**	−461.8/−163.5	91.2	28.6	26.4*
4.			E–W	**−326.0**	**−610.3**	−767.9/−352.9	129.2	21.2	87.2
5.	Wieluń	Massive	N–S	**−346.8**	**−506.7**	−696.8/−359.2	106.1	20.9	46.1
6.			E–W	**−580.0**	**−895.4**	−1098.4/−651.3	139.1	15.5	54.4
7.		Lightweight	N–S	**−447.2**	**−603.5**	−789.9/−428.2	112.6	18.7	35.0
8.			E–W	**−691.1**	**−995.1**	−1202.0/−769.1	136.7	13.7	44.0
9.	Włodawa	Massive	N–S	**−327.4**	**−496.7**	−678.1/−318.0	95.8	19.3	51.7
10.			E–W	**−546.3**	**−869.9**	−1123.6/−642.6	129.0	14.8	59.2
11.		Lightweight	N–S	**−445.0**	**−591.9**	−767.3/−403.9	102.8	17.4	33.0
12.			E–W	**−683.4**	**−969.6**	−1209.8/−730.7	129.7	13.4	41.9

TMY: Typical Meteorological Years. *averages from multiannual period are not statistically smaller than results obtained on the basis of TMY (t-test for one average, confidence level 0.95).
Note: Bold faces are basic compared values.

temperature exceeded 26°C. The available cooling power output was controlled on the basis of the outdoor temperature, with the maximum value being achieved at the design outdoor temperature in summer (20°C). The power control curve was a similar polyline as for the heating system, with constant values for the outside temperature below 16°C and above 20°C. The cooling system was working from May to September. Heating and cooling demand was calculated without taking into account the efficiency of the installation systems.

To check the dependence of results on the room casing, two versions of building partitions were adopted: massive (masonry walls insulated with the ETICS system and reinforced concrete ceilings) and

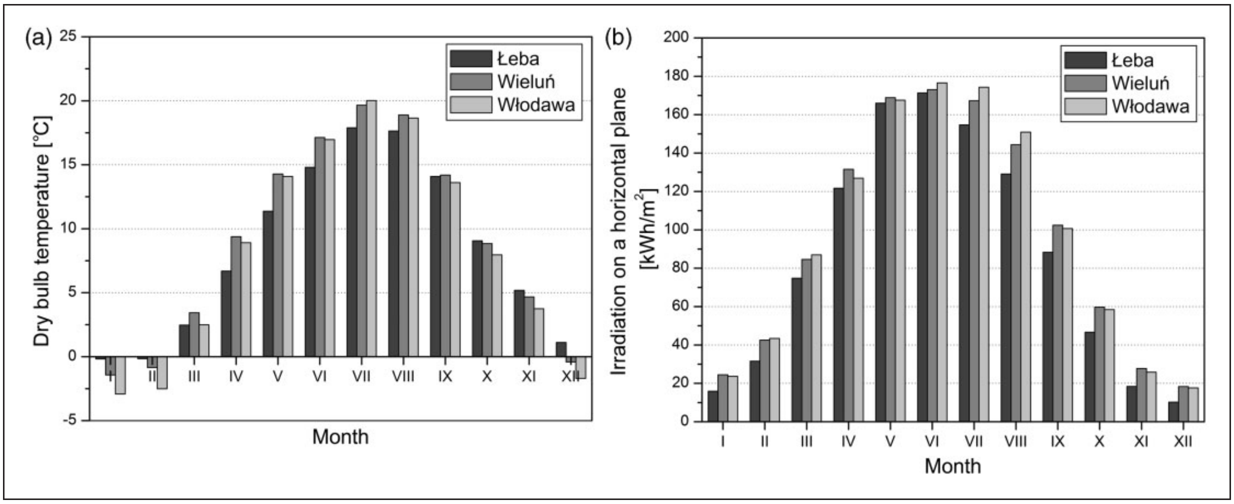

Figure 5. Comparison of multiannual characteristics of basic climatic parameters in the chosen localities: (a) monthly mean values of dry bulb temperatures and (b) sums of solar irradiation on a horizontal plane.

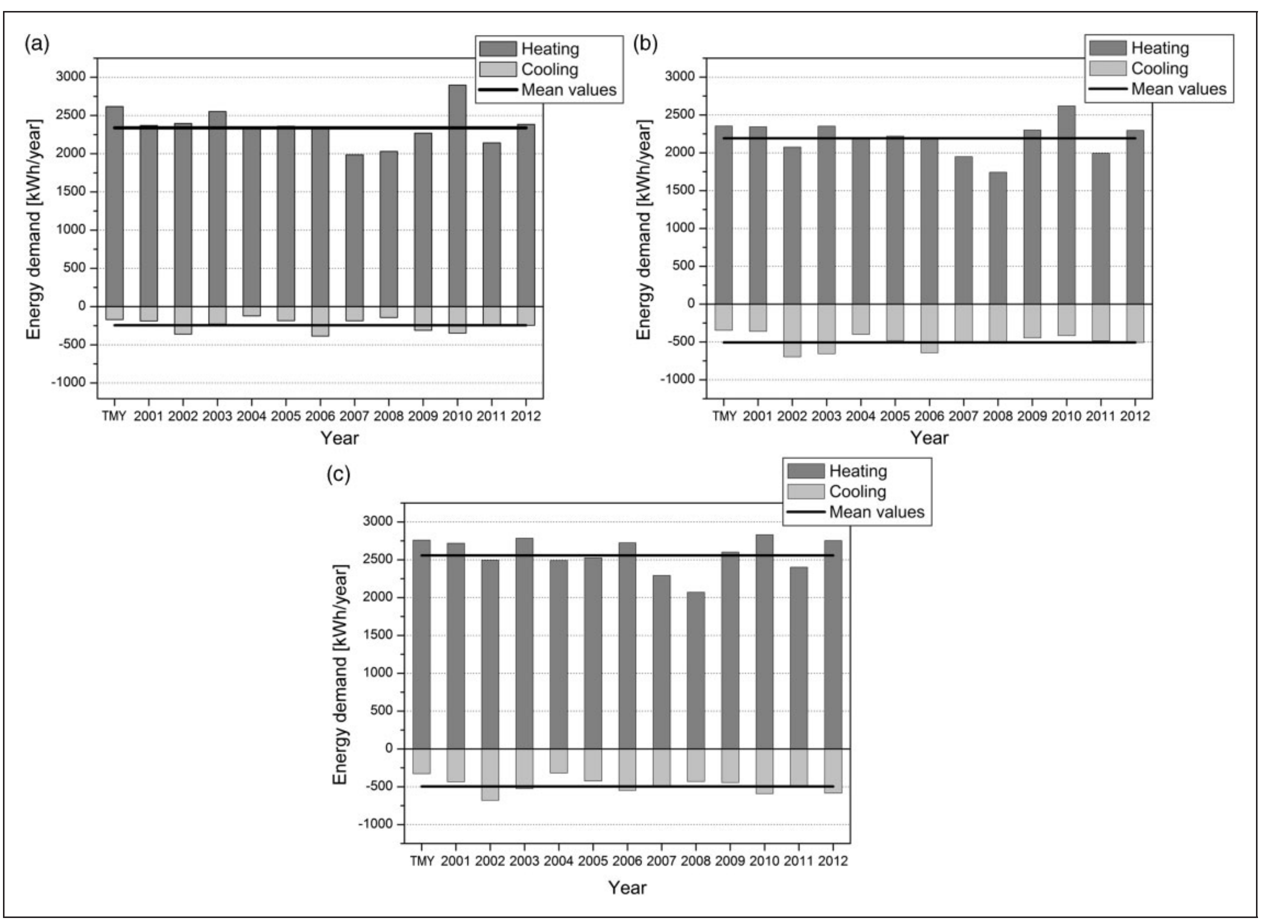

Figure 6. Heating and cooling demand for the analysed climatic data, building construction – massive, windows orientation N–S: (a) Łeba, (b) Wieluń and (c) Włodawa.

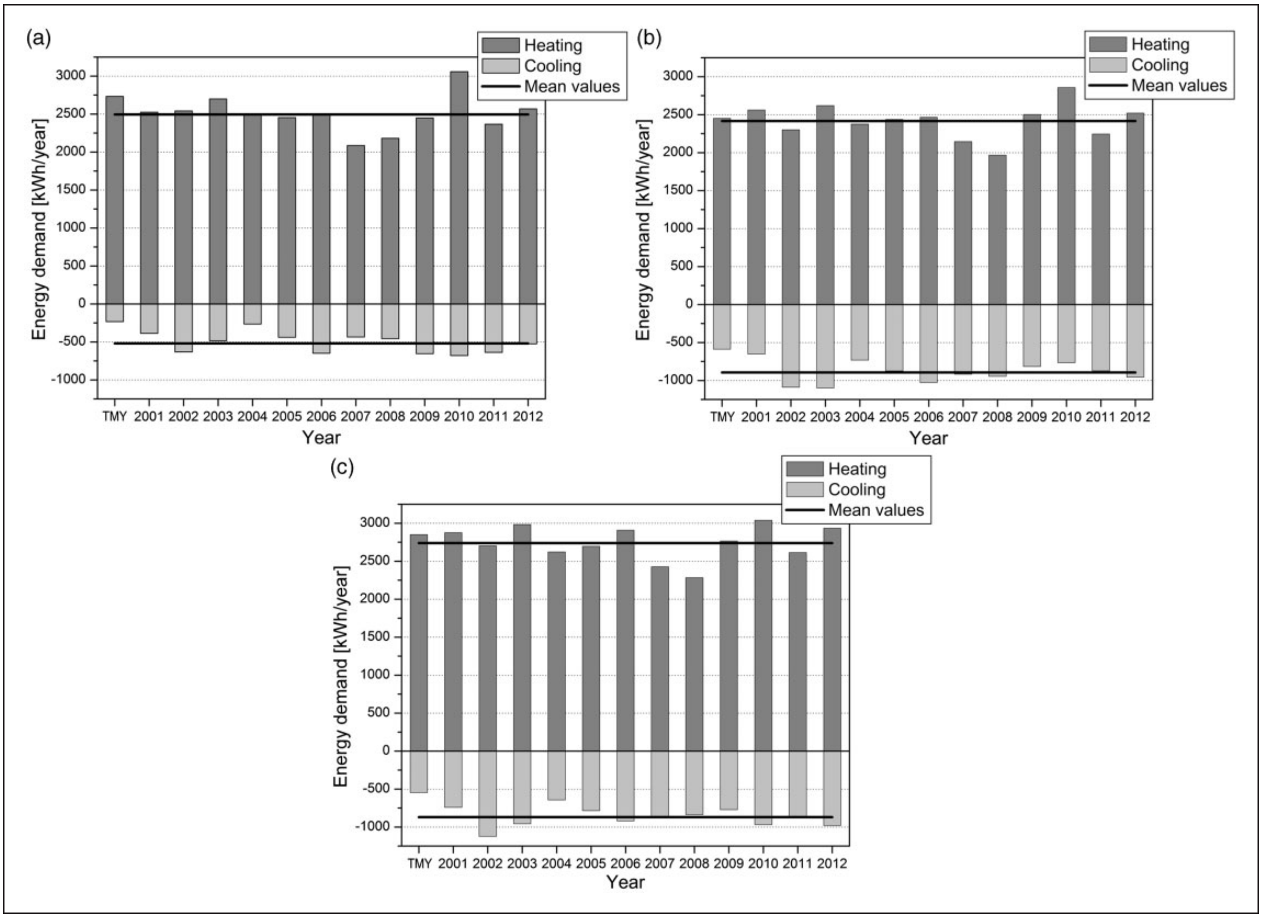

Figure 7. Heating and cooling demand for the analysed climatic data, building construction – massive, windows orientation E−W: (a) Łeba, (b) Wieluń and (c) Włodawa.

lightweight (wooden framework with mineral wool as thermal insulation). The heat capacity of the envelope, related to the floor area, was 726.0 kJ/m^{2}K and 255.2 kJ/m^{2}K, respectively. The windows were facing north and south or east and west, allowing for sensitivity analysis of the results due to various solar irradiation. Radiation incident on horizontal surfaces was calculated using an anisotropic diffuse radiation model developed by Perez et al.[27] This model proved to be consistent with the results of the measurements taken in Poland.[28]

Presentation and discussion of research results

For different types of apartments, heating and cooling demand were determined on the basis of the climatic data of the TMY and the data from the later comparative period of 2001–2012. Altogether, over 150 computer simulations of the annual cycle of the object's functioning were carried out. The chosen results are presented in Tables 6 and 7 and Figures 5–8.

Heating demand

Wieluń, lying in the middle part of Poland within the second climatic zone, turned out to be a locality with the smallest heating demand. In the autumnal and wintry period (October–February), the place has intermediate outdoor air temperatures, but its insolation is the greatest out of the presented locations. Also, it has the greatest share of directional solar radiation. In the spring season (March, April, May), insolation and outside temperatures are the highest, which altogether provides very favourable conditions as regards energy consumption (Figure 5). The coastal zone, represented by Łeba, in spite of the highest temperatures from October to February, turned out to be a less favourable location, mostly due to the smallest solar radiation intensity. In the eastern part of Poland (Włodawa), temperatures from September to February are the lowest and, in spite of quite high solar radiation intensity, this region has the greatest energy demand. Differences between extreme cases amount to 12.8% to 16.7%.

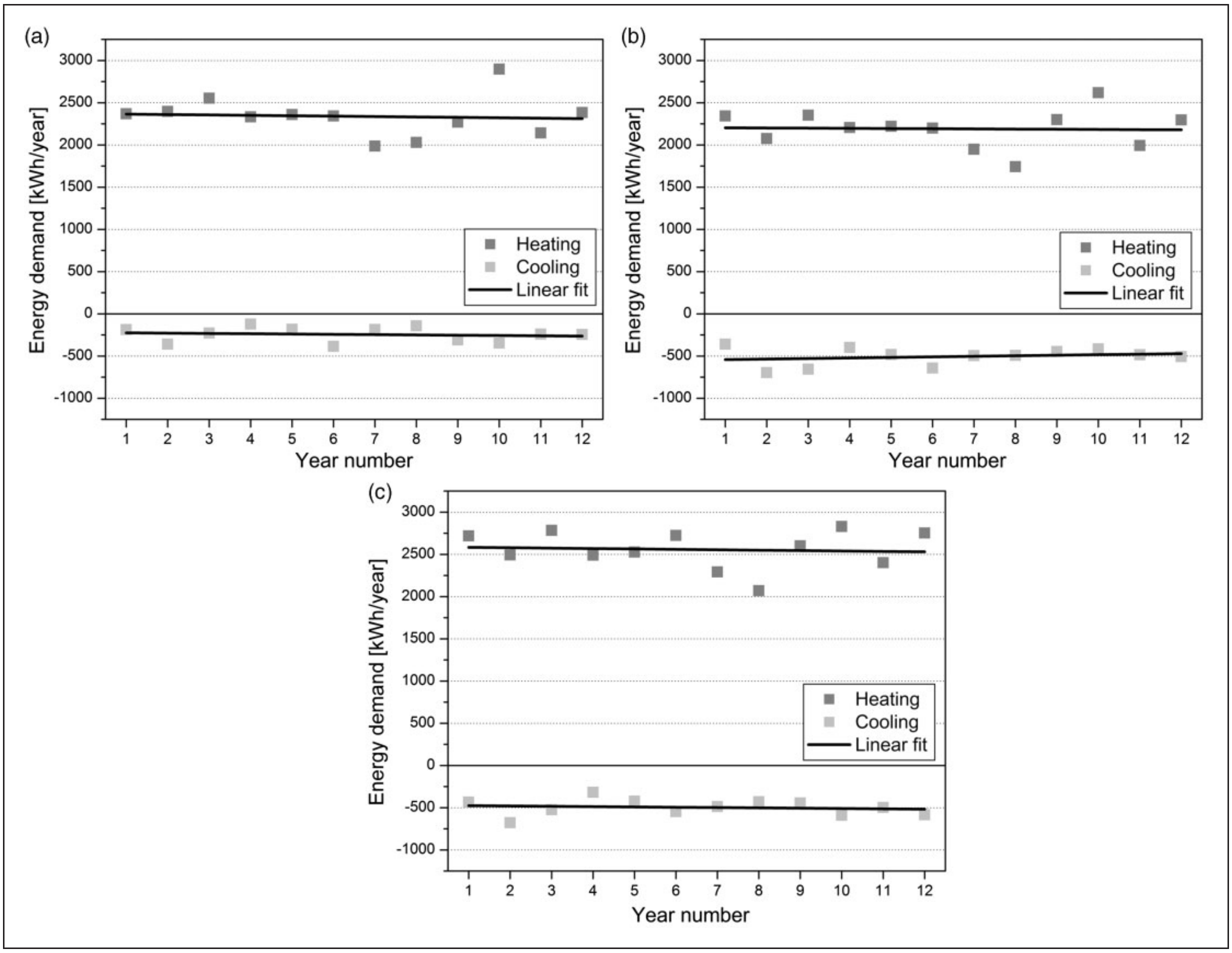

Figure 8. Heating and cooling demand from 2001 to 2012 and the trend lines obtained with the method of least squares, building construction – massive, windows orientation N–S: (a) Łeba, (b) Wieluń and (c) Włodawa.

Qualitative nature of the results from 2001 to 2012 was similar in all of the cases. The highest energy need occurred in 2010, the year with the lowest average temperature during the heating season. In the years 2007 and 2008, heating demand was the lowest, because of the highest average temperature between September and May.

Irrespective of locality and type of construction, greater heating demand was achieved in the cases of windows facing east–west. Since the apartment layout and windows arrangement are symmetrical, this would be caused exclusively by environmental factors, thus smaller insolation of the elevation in the winter. Differences were connected with the change of orientation which would be greatest for the locality with the highest solar radiation intensity, i.e. Wieluń, and they amounted to 10.3% for massive structures and 8.7% for light-weight structures. In the remaining places they ranged between 5.8% and 7.1%.

The thermal capacity of the flat's envelope turned out to be the factor of the smallest significance for heating demand, and the differences between light-weight structures and massive structures were from 1.4% to 3.8%. The effects of variations in thermal capacity were more conspicuous for apartments with windows facing north and south due to greater gains from solar radiation falling on the southern elevation. These differences are, however, not big, and even the envelope of diminished accumulation abilities proved sufficient for the effective use of heat gains.

Comparing the results obtained on the basis of both sets of climatic data, it was ascertained that heating demand determined in the period of 2001–2012 was, for each variant of an apartment, smaller than in the preceding 30 years which are represented by TMY (Figures 6 and 7). Because of the rise in temperature and intensity of solar radiation, not only the resultant energy need but also the components of the energy balance would vary. Average transmission and ventilation losses during 2001–2012 were up to 2.3% and 1.9% smaller than the equivalent losses calculated with the use of TMY. At the same time, solar gains in the

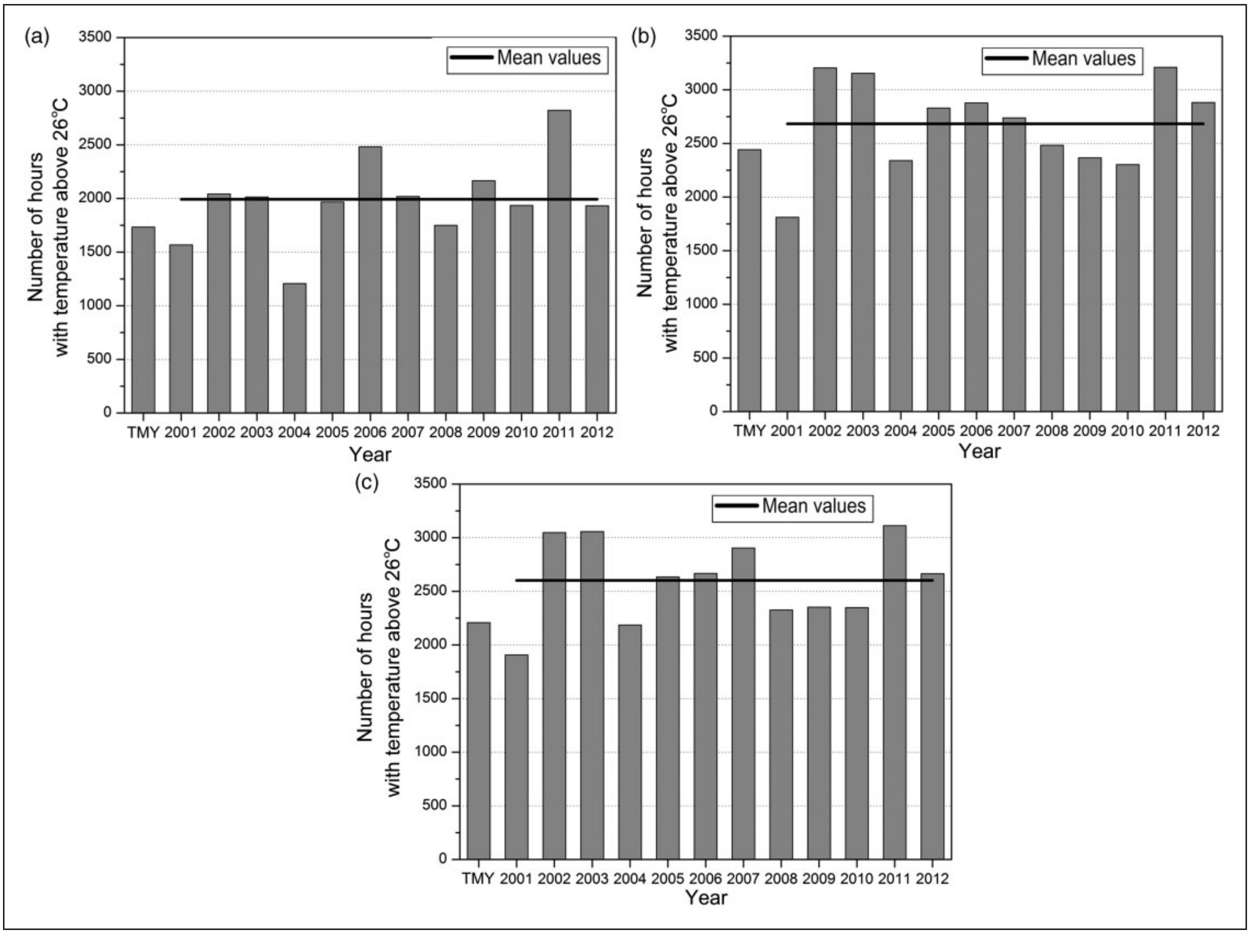

Figure 9. Number of hours with internal temperature above 26°C, building construction – massive, windows orientation N–S: (a) Łeba, (b) Wieluń and (c) Włodawa.

apartment increased on average by 17.1%, causing a reduction in demand for heating compared with TMY.

For the north-south direction the fall in energy demand was higher, and ranged between 6.0% and 10.6%, while for the east–west direction, it ranged between 1.7% and 9.0% (Table 6). These differences are caused, above all, by a greater share of directional radiation in real climatic data than in TMY. In the winter, the southern orientation enables a more effective use of this radiation due to small incident angles, in particular, in conjunction with the greater accumulation possibilities of a massive structure.

On the basis of the Shapiro–Wilk test, the hypothesis about a normal distribution of energy demand from the comparative period of 2001–2012 cannot be rejected. For all variants of apartments a statistical *t*-test was carried out for one average, comparing multiannual averages and amounts of heating demand determined with the help of TMY. At a confidence level of 0.95, this test proved that 50% of the averages obtained for the subsequent period are statistically smaller than the results achieved on the basis of TMY (results marked with * in Table 6 have not met this requirement). Moreover, the lines of the tendency set with the least-squares method in 9 out of 12 analysed cases showed the downward trend of heating demand (Figure 8). This suggests the possibility of a further reduction in future heating demand. Nevertheless, according to the authors of the present article, because of the relatively small differences between the results obtained from TMY and those from the later periods and general data availability, TMY can be used for determining the heating demand of buildings constructed after 2000 and those designed in the years to come.

Cooling demand

The area of central and eastern Poland has considerable insolation during the summer, which finds its reflection in the greatest values of cooling demand achieved for Wieluń and Włodawa. From June to August, this region has the highest temperatures of outdoor air, and solar radiation intensity achieves the highest values (Figure 5), while directional radiation constitutes

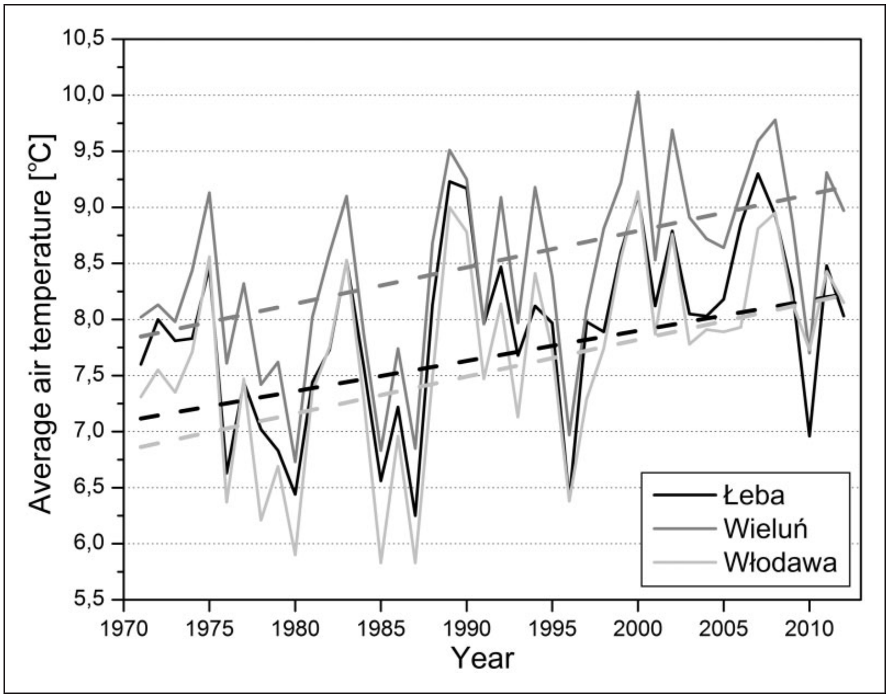

Figure 10. Average air temperature from 1971 to 2012 and the trend lines obtained with the method of least squares.

almost 60% of it. Because of the lowest temperatures and the smallest insolation, energy demand for Łeba is, on average, half as big. Regional differences are much bigger than in the heating season and they equal, depending on the apartment orientation and construction, from 38.7% to 51.7%.

In all of the localities, the highest cooling demand was observed in 2002, the lowest in 2004. Years of extreme values do not coincide with heating demand. The year 2002 had the highest average temperature in summer, while 2004 was the year of the lowest average temperature and second lowest (after 2007) insolation.

The change of window orientation can lead to a huge increase in cooling demand, and the differences between the north-south and east–west directions ranged from 63.8% to 112.7%. In the summer season, vertical surfaces facing east and west would have a greater doses of solar radiation in total than surfaces facing north and south. In conjunction with the smaller incidence angles and greater solar radiance transmission through glazing, this would give considerable heat gains.

The diminished thermal capacity of partition walls would influence energy demand to a much larger extent than in the heating season. The growth in cooling demand in rooms of light-weight envelope oriented north-south varied from 11.1% to 17.2%, and in the rooms oriented east–west from 19.1% to 30.4%. In envelopes of small capacity of heat accumulation, it is difficult to effectively make use of increased solar gains, which leads to the overheating of rooms.

The average energy demand obtained in the period of 2001–2012 was much higher than results achieved using TMY. The growth in cooling demand amounted from 26.4% to over 120%, and the most profound differences were noted in the apartment in Łeba. Within central and eastern Poland (Wieluń and Włodawa), the differences in cooling demand ranged from 33.0% to 59.2%. It is worth noticing that the absolute value of the cooling demand increase and the heating demand reduction are comparable – they amount to approximately 200 kWh/year on average. However, the proportion of cooling demand increase is much higher than the heating demand decrease, because of the much smaller absolute value of the cooling need.

Comparing the components of the energy balance calculated with the use of TMY and subsequent climate data, the same trend as for heating demand was observed. The changes were even more pronounced – average transmission and ventilation losses during 2001–2012 were by 19.0% and 8.0% smaller than the equivalent losses calculated with the use of TMY. Solar gains rose up to 25.5%, and in connection with smaller heat losses, would increase the demand for cooling compared with TMY.

As in the case of heating demand, results were compared by carrying out a *t*-test for one average. At a confidence level of 0.95, almost all of the multiannual averages (except for the one marked with * in Table 7) in a statistically significant way exceeded the results obtained with the use of TMY. Moreover, in the eight

Figure 11. Cooling systems installed in dwellings, 'Czuby' district in Lublin, Poland.

of the analysed cases, the lines of the tendency lines determined with the least-squares method showed the upward trend of cooling demand (Figure 8). Such big divergences can be caused not only by differences in both types of the worked-out climatic data but also by growing tendencies towards the change of climate. In the cooling season, insolation in all localities exceeded the values given by the TMY by more than 20%, which was reflected by increased solar gains and energy demand. Furthermore, TMY was meant to be the year most aptly representing averaged long-term conditions, and therefore the share of diffuse component would dominate in the distribution of solar radiation. In the data for the period of 2001–2012 direct radiation, the transmittance was higher due to smaller prevailing incidence angles (which is especially conspicuous if windows face east and west).

To check if the discrepancies described above could be caused by the cooling system parameters or schedule, additional simulations of a 'free-running' building were conducted. In the computer model, the cooling system was disabled, and during the summer, the building was subjected only to the natural influence of solar radiation and external temperature. As a result, the number of hours with the internal temperature above 26°C was compared with number of hours calculated for the TMY. The outcomes are compared in Figure 9.

In all cases, the average number of hours when overheating could be expected, exceeded the number of such hours showed by TMY. The differences in the least unfavourable case (presented in Figure 9) were equal to 14.9%, 9.9% and 17.8% for Łeba, Wieluń and Włodawa, respectively, and in the most unfavourable case reached 44.4% (Łeba, massive construction, windows orientation W-E).

All the described factors make disproportions in energy demand impossible to neglect. Because of a big underestimation of cooling needs and the likelihood of a boost in cooling demand in the coming years, the achieved results raise doubts as to the possibility of using TMY to analyse phenomena connected with the overheating of buildings constructed in Poland after 2000.

Summary and conclusions

In the localities described above, the mean yearly temperature shows the upward trend and the average temperature rise since 1971 to 2012 was 1.3°C (Figure 10). Since 2001 until 2012, the average temperature rise was 0.4°C.

In the common perception, these changes are noticeable as well. This especially refers to the increase of air temperature in summer and the uncomfortable overheating of residential buildings employing only natural ventilation. The authors' own observations indicate that quite a few inhabitants are planning to install, or has already installed simple cooling systems in the dwellings (Figure 11). Such tendencies are also reported in the literature.[17,19,21,29]

The analyses showed that cooling demand in summer is significantly underestimated when calculated with TMY taken as the source of climatic data. This may distort the energy needs and indoor environment conditions in summer, and create discomfort in existing and new dwellings. Therefore, updating of the calculation methodology in national legislation is highly recommended.

The discomfort caused by overheating may be less noticeable if protection systems (e.g. additional insulation, glazing that decreases solar gain, more efficient ventilation systems) are implemented in building design.[30–33] If these solutions are to be efficient and economically justified, therefore, correct evaluation of the energy needs is necessary. The reliable energy characteristics of buildings should take into account the increase of temperature, insolation and number of solar days in the past 12 years. Inclusion of this phenomena in the freely available climatic data, such as TMY, is also necessary.

Authors' contribution

The contribution of the authors in the preparation of the manuscript was approximately 75% by M. Grudzińska and 25% by E. Jakusik.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The work was financially supported by the Ministry of Science and Higher Education within the statutory research number S/14/2016 at the Lublin University of Technology.

References

1. Day T. *Degree-days: theory and application*. London: The Chartered Institution of Building Services Engineers, 2006.
2. Van Dijk H and Arkesteijn C. *Windows and space heating requirements. Parameter study leading to a simplified calculation method*. Report, International Energy Agency, Annex XII, Windows and Fenestration, Delft, 1987.
3. PN – EN ISO 13790:2009. *Energy performance of buildings – Calculation of energy use for space heating and cooling*. Geneva: International Organization for Standardization, 2009.
4. Clarke JA. *Energy simulation in building design*. Oxford: Butterworth-Heinemann, 2001.
5. Crawley DB, Hand JW, Kummert M and Griffith BT. Contrasting the capabilities of building energy performance simulation programs. *Build Environ* 2008; 43: 661–673.
6. Crawley DB. Which weather data should you use for energy simulations of commercial buildings? *ASHRAE Trans* 1998; 104: 1–18.
7. Yang L, Lam JC, Liu J and Tsang CL. Building energy simulation using multi-years and typical meteorological years in different climates. *Energy Conver Manage* 2008; 49: 113–124.
8. Lund H and Eidorff S. *Selection methods for productions of Test Reference Years*. Thermal Insulation Laboratory, Technical University of Denmark, EUR 7306 EN Final Report, Short Version, Lyngby, 1981.
9. *Typical Meteorological Year user's manual*. Asheville, NC: National Climatic Data Center, U.S. Department of Commerce, 1981.
10. Crow LW. Weather year for energy calculations. *ASHRAE J* 1984; 26: 42–47.
11. Lund H. *The Design Reference Year user's manual*. Thermal Insulation Laboratory, Report No. 274, Technical University of Denmark, Lyngby, 1995.
12. Huang J. The impact of different weather data on simulated residential heating and cooling loads. *ASHRAE Trans* 1998; 104: 516–527.
13. Kershaw T, Eames M and Coley D. Comparison of multi-year and reference year building simulations. *Build Serv Eng Res Technol* 2010; 31: 357–369.
14. EN ISO 15927–4:2007. *Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4. Data for assessing the annual energy for cooling and heating systems*. Geneva: International Organization for Standardization, 2007.
15. Solomon S, Qin D, Manning M, Marquis M, Averyt K, Tignor M, Miller HL and Chen Z. *Climate change 2007: The physical science basis*. Report, Cambridge University Press, Cambridge, 2007.
16. Hulme M, Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, Lowe J, Murphy JM, Hassell D, Boorman P, McDonald R and Hill S. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 2002.
17. Collins L, Natarajan S and Levermore G. Climate change and future energy consumption in UK housing stock. *Build Serv Eng Res Technol* 2010; 31: 75–90.
18. Chow D and Levermore GJ. The effects of future climate change on heating and cooling demands in office buildings in the UK. *Build Serv Eng Res Technol* 2010; 31: 307–323.
19. Porritt S, Shao L, Cropper P and Goodier C. Adapting dwellings for heat waves. *Sustain Cities Soc* 2011; 1: 81–90.
20. Lomas KJ and Kane T. Summertime temperatures and thermal comfort in UK homes. *Build Res Inform* 2013; 41: 259–280.
21. Beizaee A, Lomas KJ and Firth SK. National survey of summertime temperatures and overheating risk in English homes. *Build Environ* 2013; 65: 1–17.
22. PN – 74/B – 02403. *Heating. Exterior calculated temperatures*. Warsaw: Standards Publishing House, 1974.
23. Baranowski D. The climate of Łeba. *Baltic Coast Zone* 2008; 12: 75–84.
24. Romer E. Polish climatic regions. *PWTN, Series B* 1949; 16: 5–27.
25. Wittchen KB, Johnsen K and Grau K. *BSim user's guide*. Hørsholm: Danish Building Research Institute, 2004.
26. PN – EN ISO 13789:2007. *Thermal performance of buildings. Transmission and ventilation heat transfer coefficients. Calculation method*. Geneva: International Organization for Standardization, 2007.
27. Perez R, Ineichen P, Seals R, Michalsky J and Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy* 1990; 44: 271–289.
28. Włodarczyk D and Nowak H. Statistical analysis of solar radiation models onto inclined planes for climatic conditions of Lower Silesia in Poland. *Archiv Civil Mech Eng* 2009; 9: 305–310.

29. Peacock AD, Jenkins DP and Kane D. Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy* 2010; 38: 3277–3288.
30. Porritt SM, Cropper PC, Shao L and Goodier CI. Heat wave adaptations for UK dwellings and introducing a retrofit toolkit. *Int J Disaster Resil Built Environ* 2013; 4: 269–286.
31. Porritt SM, Cropper PC, Shao L and Goodier CI. Ranking of interventions to reduce dwelling overheating during heat waves. *Energy Build* 2012; 55: 16–26.
32. Gupta R and Gregg M. Using UK climate change projections to adapt existing English homes for a warming climate. *Build Environ* 2012; 55: 20–42.
33. Coley D, Kershaw T and Eames M. A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures. *Build Environ* 2012; 55: 159–166.