"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
*http://enviro.vgtu.lt*

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.261
DOI: https://doi.org/10.3846/enviro.2017.261

# Methods for Improving Energy Performance of Single-family Buildings in Poland's Climatic Conditions

Hanna Jędrzejuk[1], Maciej Jaworski[2] , Michał Chwieduk[3]

*Institute of Heat Engineerind, Faculty of Power and Aeronautical Engineering,*
*Warsaw University of Technology, Warsaw, Poland*
*E-mails: [1]Hanna.Jedrzejuk@itc.pw.edu.pl (corresponding author);[2]Maciej.Jaworski@itc.pw.edu.pl;*
*[3]Michal.Chwieduk@itc.pw.edu.pl*

**Abstract.** The effect of standard means of thermal upgrading of buildings on energy performance indices is studied in the paper. The following was considered: improving thermal performance of the envelope (walls, roof, floors over unheated cellars or ground-floor slabs, windows, and doors); using exterior blinds during heating and cooling seasons; using heat recovery (recuperation) in a forced ventilation system; reducing the ventilation air flow rate; and improving air-tightness of a building. The calculations were performed for a number of variants. Seven locations in Poland were selected based on outdoor climate conditions. Various standards of thermal performance of the building envelope, internal heat capacities, and ventilation rates were applied. Variations in internal heat gains, depending on the presence of occupants (heat gains from occupants and from lighting) were considered. Due to a dynamic nature of the energy processes that take place in a building, the simplified hourly method 5R1C was used in calculations. It was verified whether single-family buildings constructed in a way that is typically found in Poland, i.e. buildings with very high heat capacity and equipped with a forced ventilation system, can meet more stringent energy performance requirements.

**Keywords:** energy-efficient buildings, thermomodernization, single family buildings.

**Conference topic:** Energy for Buildings.

## Introduction

With reference to residential buildings in Poland, energy efficiency is determined using indices of annual demand for non-renewable energy, including: primary energy (EP), final energy (EK), and effective energy (EU) for heating, cooling, and hot water preparation (MID 2015). The paper focuses on analyzing opportunities for decreasing the demand for effective energy used for heating and cooling by applying standard means of thermal upgrading.

In existing buildings possible changes which lead to improving the energy performance of a residential building include:

- improving thermal performance of the envelope, including walls, the roof, and ceilings over a heated area and unheated rooms;
- replacement of windows and exterior doors;
- using exterior blinds during certain periods;
- using forced ventilation with heat recovery;
- decreasing the ventilation air flow rate during the absence of occupants.

## Calculation method and assessment indices

To determine effective energy demand for heating and cooling, the simplified hourly method 5R1C was used according to the algorithm provided in PN-EN ISO 13790:2009. By this method the following can be determined: annual effective energy demand for heating ($Q_{nd,h}$), and annual effective energy demand for cooling ($Q_{nd,c}$); and, in relation to the area of thermally conditioned space, an index of annual effective energy demand for heating ($EU_h$), and an index of annual effective energy demand for cooling ($EU_c$). The values of these indices show the energy performance of the building being evaluated.

## Data and control rules applied in calculations

The impact of thermal upgrading initiatives on energy efficiency was studied with respect to a middle-sized single-family building with a total useful floor area of 150 m$^2$. The area of transparent partitions was taken according to minimum technical requirements as one eighth of the useful floor area. It was assumed that the areas of the south and north elevations each make up 30%, and the areas of the east and west ones each make up 20% of the area of external walls. The area of windows was assumed to make up: 40% of the area of the south elevation, and 10% of the north elevation; 25% of the area of each of the east and west elevations. The building is occupied by four inhabitants. The temperature setpoint in the heating season is 20 °C, and in the cooling season 26 °C. Artificial lighting is turned on when solar irradiance is less than 70 W $m^{-2}$ and when there are occupants in the building according to the occupancy pattern used. When solar irradiance exceeds 300 $Wm^{-2}$, exterior blinds, with the efficiency of 40%, can be used to prevent rooms from overheating. In the heating season, with temperatures below 0 °C, between 10 p.m. and 6 a.m. the next day, exterior foldable plastic blinds, filled with foam characterized by medium air permeability, which improve thermal performance of windows, can be used. A change in the index was determined according to PN–EN ISO 10077-1:2006.

Thermal performance variants were taken according to technical requirements in force in Poland in 1982, 1991, 2002, 2014, 2017, and 2021. They are listed in Table 1.

Table 1. Thermal insulation of external partitions (overall heat transfer coefficient) (PN-B-02020:1982; PN-B-02020:1991; MI 2002)

| Type of partition | Standard of thermal performance of selected partitions [W m–2 K–1] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1982 | 1991 | 2002 | 2008 | 2104 | 2017 | 2021 |
| External walls (Θi ≥ 16 °C) | 0.75 | 0.55 | 0.30 | 0.30 | 0.25 | 0.23 | 0.20 |
| Roofs, deck roofs and floors under unheated attic spaces and over passages (Θi ≥ 16 °C) | 0.45 | 0.30 | 0.30 | 0.25 | 0.20 | 0.18 | 0.15 |
| Floors over unheated rooms and closed crawl spaces (Θi ≥ 16 °C) | 1.00 | 0.60 | 0.60 | 0.45 | 0.25 | 0.25 | 0.25 |
| Windows (Θi ≥ 16 °C) | 2.60 | 2.60 | 2.60 | 1.70 / 1.80 | 1.30 | 1.10 | 0.90 |
| External doors | 2.50 | 3.00 | 3.00 | 2.60 | 1.70 | 1.50 | 1.30 |

The type of ventilation system and the air change rate have considerable effect on energy demand for heating and cooling, which is why the following variants of air change rates were assumed: 0.5 $h^{-1}$, 1.5 $h^{-1}$, 2.5 $h^{-1}$, and 4.0 $h^{-1}$.

Where recuperation is used in a forced ventilation system, the temperature efficiency of the heat exchanger was taken as 60%. It is slightly lower than that used in (Grzebielec *et al.* 2014).

In the 5R1C method (PN-EN ISO 13790:2009), dynamic properties of a building are described by internal heat capacity of a building and the internal heat transfer surface area ($A_f$) (Table 2). A traditional construction of external walls, i.e. a brickwork wall or a hollow clay block wall, characterized by a very high internal heat capacity, is the most common one in Poland. Therefore, the "F" class, comprising buildings of an ultra heavy construction, was added in Table 2.

Table 2. Internal heat capacity (PN-EN ISO 13790:2009)

| Type | Building class | Internal heat transfer surface area $A_m$, [$m^2$] | Internal heat capacity $C_m$, [J/K] |
|---|---|---|---|
| A | Very light | 2.5 $A_f$ | 80,000 $A_f$ |
| B | Light | 2.5 $A_f$ | 110,000 $A_f$ |
| C | Medium | 2.5 $A_f$ | 165,000 $A_f$ |
| D | Heavy | 3.0 $A_f$ | 260,000 $A_f$ |
| E | Very heavy | 3.5 $A_f$ | 370,000 $A_f$ |
| F | Ultra heavy (PL) | 3.5 $A_f$ | 550,000 $A_f$ |

**Meteorological data**

Meteorological data prepared for 61 stations are obligatorily used for energy calculations in Poland (MIC 2017). For the purpose of the study a set of locations was chosen in which basic climatic conditions or their annual amplitudes take extreme values (Table 3).

Statistical meteorological data indicate that the largest variations of monthly average outdoor air temperatures occur in Przemyśl, while the smallest in Gdańsk. The lowest annual average outdoor air temperatures are observed in Zakopane, and the highest in Legnica. The highest monthly average air temperatures are recorded in Nowy Sącz, while the lowest in Suwałki. In terms of insolation, unfavourable conditions occur in Chojnice, while the most favourable in Przemyśl. The largest number of heating degree days is reported in Zakopane, and the smallest one in Gdańsk. The largest number of cooling degree days occur in Legnica, and the smallest one in Zakopane.

Table 3. Basic climatic conditions from selected meteorological stations (MIC 2017)

| Location | Deviation of max. monthly average temperature from annual average | Annual average dry-bulb temperature | Max. monthly average dry-bulb temperature | Min. monthly average dry-bulb temperature | Total annual solar irradiance per unit area of a horizontal surface | Heating degree days (Qint,h = 18 °C) / Cooling degree days (Qint,h = 26 °C) |
|---|---|---|---|---|---|---|
| [-] | [°C] | [°C] | [°C] | [°C] | [kWh m–²] | [°Kh / °K h] |
| Chojnice | 10.9 | 7.1 | 16.5 | –3.8 | 803.1 (MIN) | 97,600.1 / 83.0 |
| Gdańsk Port Północny | 7.5 (MIN) | 8.7 | 18.7 | 1.2 (MAX) | 886.4 | 83,074.2 / 37.0 |
| Legnica | 9.8 | 9.0 (MAX) | 18.5 | –0.8 | 918.3 | 83,308.2 / 376.3 |
| Nowy Sącz | 8.0 | 8.5 | 19.7 (MAX) | 0.5 | 1,061.5 | 87,643.8 / 259.6 |
| Przemyśl | 12.5 (MAX) | 7.6 | 18.0 | –4.9 | 1,072.3 (MAX) | 94,015.9 / 78.3 |
| Suwałki | 11.6 | 6.3 | 16.1 | –5.3 (MIN) | 837.5 | 105,000.1 / 179.0 |
| Zakopane | 8.4 | 5.4 (MIN) | 14.3 (MIN) | –3.0 | 1,006.7 | 110,956.9 (MAX) / 1.7 (MIN) |

**Results of a simulation-based analysis**

A total of 1344 simulations were performed using the 5R1C model. This way the values of effective energy demand for heating and cooling were obtained. Sample results of a simulation used for studying the effect of the air change rate and internal heat capacity on the index of annual energy demand for heating with the "1982" standard of thermal performance of the envelope (Table 1) are listed in Table 4.

Table 4. The effect of the air change rate and internal heat capacity on the index of annual energy demand for heating ($EU_h$) (location: Chojnice, the "1982" standard of thermal performance)

| Thermal performance standard | Air change rate | Internal heat capacity class | | | | | | Relative change in % between max. and min. values |
|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | |
| [year] | [h–1] | EUh [kWh m–2 a–1] | | | | | | % |
| 1982 | 0.5 | 144.78 | 144.36 | 142.83 | 141.16 | 140.66 | 140.17 | 3.18 |
| | 1.5 | 172.44 | 171.8 | 170.63 | 169.37 | 168.75 | 168.11 | 2.51 |
| | 2.5 | 200.37 | 199.52 | 198.68 | 197.78 | 197.03 | 196.28 | 2.04 |
| | 4.0 | 242.61 | 241.53 | 241.04 | 240.63 | 239.7 | 238.76 | 1.59 |

The data above can lead to a conclusion that the air change rate (and thus the ventilation air flow rate), even in the case of a building with a low thermal performance, has a considerable effect on the index of annual energy demand for heating ($EU_h$). The higher internal heat capacity a building has, the better index $EU_h$ it achieves, although this effect is not substantial. The percentage difference between values of the index varies from about 1.6% (4.0 $h^{-1}$) to about 3.2% (0.5 $h^{-1}$).

Selected calculation results for each of seven locations and for each thermal improvement variant are listed below in Tables 5 to 13. The tables include values of the maximum and minimum indices of annual effective energy demand for heating (MAX $EU_h$ and MIN $EU_h$, respectively) and cooling (MAX $EU_c$ and MIN $EU_c$, respectively) and the ratio of the minimum and maximum indices as a percentage ($\Delta_h$ in % and $\Delta_c$ in %, respectively).

Table 5. Maximum and minimum indices of annual energy demand for heating and cooling. The analysis of the impact of thermal performance (variables: location, internal heat capacity, air change rate)

| Assessment index | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| | $EU_h$ [kWh $m^{-2}$ $a^{-1}$] | | | | | | |
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 525.98 | 447.37 | 444.86 | 461.81 | 497.76 | 565.24 | 586.70 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 54.63 | 41.68 | 41.14 | 42.50 | 51.12 | 66.40 | 55.66 |
| $\Delta_h$ [%] | 10.39 | 9.32 | 9.25 | 9.55 | 10.27 | 11.75 | 9.49 |
| MAX $EU_c$ [kWh $a^{-1}$ $m^{-2}$] | 15.29 | 19.04 | 21.76 | 24.91 | 26.08 | 18.12 | 13.06 |
| MIN EUc [kWh $a^{-1}$ $m^{-2}$] | 0.10 | 0.27 | 1.67 | 1.44 | 0.88 | 0.33 | 0.00 |
| $\Delta_c$ [%] | 0.65 | 1.42 | 7.67 | 5.78 | 3.37 | 1.82 | 0.00 |

Table 5 lists the values of the indices of energy demand for heating and cooling in selected locations for a number of thermal performance standards and various air change rates in a building.

In all the locations (Table 5) maximum values of $EU_h$ occur for the lowest thermal performance standard (1982), the lowest internal heat capacity (A), and the highest air change rate (4.0 $h^{-1}$). Minimum values of MIN $EU_h$ are found for the highest thermal performance standard (2021), the highest internal heat capacity (F), and the lowest air change rate (0.5 $h^{-1}$). As for heating, minimum values account for about 10% of maximum values. This means that by improving thermal performance of the envelope from the lowest standard (1982) to the highest one and decreasing the ventilation air flow rate, $EU_h$ can be decreased by about 90%.

In the case of cooling, maximum values of the index of energy demand for cooling ($EU_c$) occur for the highest thermal performance standard (2021), the lowest heat capacity (A), and the lowest air change rate (0.5 $h^{-1}$). Minimum values of this index are found for the "2002" thermal performance standard, the highest air change rate (4.0 $h^{-1}$), and the highest internal heat capacity (F). Consequently, excess heat gains can be removed from a building mainly by increasing the ventilation rate. Results for Zakopane are slightly different (Table 6). Due to specific outdoor climate conditions, independently of the thermal performance standard, there is no need for cooling in buildings with internal heat capacity class "E" and "F", provided that the air change rate is not lower than 1.5 $h^{-1}$. Also in the case of class "C" buildings, i.e. with medium heat capacity, cooling is not required provided that the air change rate is not lower than 2.5 $h^{-1}$.

Table 6. The effect of the air change rate, internal heat capacity, and the thermal performance standard on the index of annual energy demand for cooling ($EU_c$) (location: Zakopane)

| Thermal performance standard | Air change rate [$h^{-1}$] | Internal heat capacity | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F |
| | | $EU_c$ [kWh $m^{-2}$ $a^{-1}$] | | | | | |
| 1982 | 0.5 | 1.22 | 0.82 | 0.45 | 0.18 | 0.07 | 0.02 |
| | 1.5 | 0.62 | 0.31 | 0.09 | 0.01 | 0.00 | 0.00 |
| | 2.5 | 0.40 | 0.15 | 0.03 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.29 | 0.08 | 0.01 | 0.00 | 0.00 | 0.00 |
| 1991 | 0.5 | 1.44 | 1.04 | 0.65 | 0.33 | 0.17 | 0.08 |
| | 1.5 | 0.57 | 0.29 | 0.09 | 0.01 | 0.00 | 0.00 |
| | 2.5 | 0.32 | 0.11 | 0.02 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.20 | 0.05 | 0.01 | 0.00 | 0.00 | 0.00 |
| 2002 | 0.5 | 1.70 | 1.32 | 0.91 | 0.54 | 0.34 | 0.20 |
| | 1.5 | 0.50 | 0.26 | 0.08 | 0.01 | 0.00 | 0.00 |
| | 2.5 | 0.23 | 0.07 | 0.01 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.13 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2008 | 0.5 | 2.62 | 2.17 | 1.70 | 1.25 | 0.98 | 0.73 |
| | 1.5 | 0.64 | 0.37 | 0.14 | 0.03 | 0.01 | 0.00 |
| | 2.5 | 0.28 | 0.10 | 0.02 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.15 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2014 | 0.5 | 4.22 | 3.74 | 3.20 | 2.71 | 2.42 | 2.13 |
| | 1.5 | 0.78 | 0.49 | 0.23 | 0.07 | 0.03 | 0.01 |
| | 2.5 | 0.31 | 0.12 | 0.02 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.14 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2017 | 0.5 | 4.85 | 4.38 | 3.84 | 3.32 | 3.02 | 2.75 |
| | 1.5 | 0.82 | 0.53 | 0.26 | 0.08 | 0.03 | 0.01 |
| | 2.5 | 0.31 | 0.12 | 0.02 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.14 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2021 | 0.5 | 5.96 | 5.52 | 5.02 | 4.47 | 4.15 | 3.89 |
| | 1.5 | 0.89 | 0.59 | 0.31 | 0.11 | 0.05 | 0.01 |
| | 2.5 | 0.32 | 0.13 | 0.03 | 0.00 | 0.00 | 0.00 |
| | 4.0 | 0.13 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |

In all the cases under consideration minimum values of the index of effective energy demand for cooling occur with ultra heavy constructions (F) and intense ventilation (4.0 $h^{-1}$ or even 2.5 $h^{-1}$), while maximum values are found for a class "A" building (very low internal heat capacity) with the minimum air change rate (0.5 $h^{-1}$). Using blinds at night-time has no substantial effect on decreasing the energy demand for heating. In the case considered the use of exterior blinds decreases the effective heat demand for heating, at the maximum, by only between 1.2% (Gdańsk) and 3.3% (Suwałki). The effectiveness of exterior blinds is significantly higher when they are used to prevent the rooms from overheating. Maximum drops in energy demand for cooling amount to 38.0% (Legnica) and 28.1% (Przemyśl).

Table 8 lists extreme values of energy demand indices when the ventilation air flow rate is reduced during the absence of occupants.

In all the cases (Table 8) the maximum reduction in energy demand for heating achieved by decreasing the ventilation air flow rate by 50% is similar and amounts to about 30%. It occurs for the highest ventilation air flow rate (4.0 $h^{-1}$) and the highest thermal performance standard (2021). The smallest impact on the reduction of energy demand for heating, i.e. about. 8%, was found for the lowest ventilation air flow rate (0.5 $h^{-1}$) and the lowest thermal performance standard (1982). The index of energy demand for cooling EUc is the highest for class A buildings (very light design), the least intense ventilation (0.5 $h^{-1}$), and the highest thermal performance standard (2021).

The lowest values of this index were obtained for class F buildings (ultra heavy design) with intense ventilation (2.5 $h^{-1}$ or 4.0 $h^{-1}$). In the case of the Zakopane location (Tab. 6) and the highest internal heat capacity (F), the thermal performance standard is practically not relevant. The $EU_c$ index takes maximum values only for the air change rate of 0.5 $h^{-1}$.

Table 7 lists extreme values of energy demand indices when exterior blinds are used, designed to provide thermal protection in winter and to prevent exposure to excess sunlight in summer.

In all the cases (Table 7) the maximum reduction in energy demand for heating achieved by decreasing the ventilation air flow rate by 50% is similar and amounts to about 30%. It occurs for the highest ventilation air flow rate (4.0 $h^{-1}$) and the highest thermal performance standard (2021). The smallest impact on the reduction of energy demand for heating, i.e. about. 8%, was found for the lowest ventilation air flow rate (0.5 $h^{-1}$) and the lowest thermal performance standard (1982). The index of energy demand for cooling $EU_c$ is the highest for class "A" buildings (very light design), the least intense ventilation (0.5 $h^{-1}$), and the highest thermal performance standard (2021).

The lowest values of this index were obtained for class "F" buildings (ultra heavy design) with intense ventilation (2.5 $h^{-1}$ or 4.0 $h^{-1}$). In the case of the Zakopane location (Table 6) and the highest internal heat capacity (F), the thermal performance standard is practically not relevant. The $EU_c$ index takes maximum values only for the air change rate of 0.5 $h^{-1}$.

Reducing the ventilation air flow rate results in a 1.1 to 3.26-fold increase in energy demand for cooling (Table 9) as compared to a building where the air flow rate is 100%. In summer, when internal heat gains occur, the reduction in the ventilation air flow rate results in an increase in energy demand for cooling.

Table 10 reports extreme values of energy demand indices when heat recovery is used in a forced ventilation system. The $EU_h$ index takes the highest values for buildings with the lowest thermal performance standard (1982) and the lowest air change rate (0.5 $h^{-1}$). This index is only slightly related to the internal heat capacity (a change by about 3%). It can be expected that the energy performance of buildings with a low thermal protection standard can be improved by about 17%. For buildings with a high thermal performance standard and the high air change rate (4.0 $h^{-1}$) the decrease in the energy performance index amounts to about 60%, and with a low air change rate to about 40%.

In the cooling season the use of recuperation in a forced ventilation system results in an increase in energy demand for cooling.

Table 7. Maximum and minimum indices of annual energy demand for heating and cooling. The analysis of the impact of exterior blinds (variables: location, internal heat capacity, air change rate, thermal performance standard)

| Assessment index | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 523.98 | 446.45 | 443.55 | 460.08 | 495.38 | 562.58 | 583.69 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 54.03 | 41.43 | 40.80 | 41.98 | 50.48 | 65.62 | 54.78 |
| $\Delta_h$ [%] | 10.31 | 9.28 | 9.20 | 9.12 | 10.19 | 11.66 | 9.39 |
| MAX $EU_c$ [kWh $a^{-1}$ $m^{-2}$] | 8.47 | 11.22 | 13.38 | 14.38 | 15.10 | 9.58 | 5.96 |
| MIN EUc [kWh $a^{-1}$ $m^{-2}$] | 0.02 | 0.02 | 0.84 | 0.72 | 0.30 | 0.08 | 0.00 |
| $\Delta_c$ [%] | 0.24 | 0.11 | 6.28 | 5.01 | 1.99 | 0.84 | 0.00 |

Table 8. Maximum and minimum indices of annual energy demand for heating. The analysis of the impact of reducing the ventilation air flow rate by 50% (variables: location, internal heat capacity, air change rate, thermal performance standard)

| Assessment index | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 410.08 | 349.11 | 343.36 | 355.75 | 388.69 | 443.15 | 454.48 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 43.48 | 32.64 | 31.76 | 32.98 | 40.78 | 54.15 | 43.78 |
| $\Delta_h$ [%] | 10.60 | 9.35 | 9.25 | 9.27 | 10.49 | 12.22 | 9.63 |

Table 9. A relative increase in energy demand for cooling as a consequence of decreasing the ventilation air flow rate by 50%. Location: Gdańsk (variables: internal heat capacity, air change rate, thermal performance standard)

| Thermal performance standard | Air change rate [$h^{-1}$] | Internal heat capacity | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F |
| 1982 | 0.5 | 1.10 | 1.12 | 1.15 | 1.17 | 1.19 | 1.22 |
| | 1.5 | 1.18 | 1.24 | 1.33 | 1.45 | 1.56 | 1.71 |
| | 2.5 | 1.16 | 1.25 | 1.38 | 1.59 | 1.83 | 2.10 |
| | 4.0 | 1.11 | 1.18 | 1.28 | 1.48 | 1.63 | 1.84 |
| 2021 | 0.5 | 1.17 | 1.18 | 1.19 | 1.19 | 1.19 | 1.19 |
| | 1.5 | 1.49 | 1.55 | 1.61 | 1.68 | 1.72 | 1.80 |
| | 2.5 | 1.53 | 1.68 | 1.88 | 2.14 | 2.35 | 2.66 |
| | 4.0 | 1.35 | 1.51 | 1.76 | 2.13 | 2.57 | 3.26 |

Table 10. Maximum and minimum indices of annual energy demand for heating. The analysis of the impact of using heat recovery in a forced ventilation system (variables: location, heat capacity, air change rate, thermal performance standard)

| Assessment index | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 284.58 | 237.73 | 235.43 | 243.81 | 265.83 | 309.24 | 313.52 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 31.01 | 21.89 | 21.85 | 22.24 | 29.21 | 39.42 | 30.62 |
| $\Delta_h$ [%] | 10.90 | 9.21 | 9.28 | 9.12 | 10.99 | 12.75 | 9.77 |

Table 11 lists relative changes in $EU_c$. Heat recovery can even lead to an over eightfold increase in design energy demand for cooling in comparison to a building without recuperation. This is why such a solution is unacceptable for energy efficiency reasons.

Table 11. A relative increase in energy demand for cooling as a consequence of heat recovery from ventilation air. Location: Gdańsk (variables: internal heat capacity, air change rate, thermal performance standard)

| Thermal performance standard | Air change rate [$h^{-1}$] | Internal heat capacity | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F |
| 1982 | 0.5 | 1.21 | 1.24 | 1.28 | 1.32 | 1.35 | 1.39 |
| | 1.5 | 1.45 | 1.52 | 1.66 | 1.85 | 2.02 | 2.27 |
| | 2.5 | 1.44 | 1.56 | 1.79 | 2.16 | 2.60 | 3.22 |
| | 4.0 | 1.33 | 1.43 | 1.62 | 2.00 | 2.40 | 3.00 |
| 2021 | 0.5 | 1.41 | 1.43 | 1.44 | 1.45 | 1.45 | 1.44 |
| | 1.5 | 2.32 | 2.43 | 2.55 | 2.69 | 2.81 | 3.01 |
| | 2.5 | 2.75 | 3.08 | 3.61 | 4.28 | 4.85 | 5.74 |
| | 4.0 | 2.28 | 2.63 | 3.33 | 4.47 | 5.83 | 8.24 |

Table 12 reports extreme values of energy demand indices when the ventilation air flow rate is reduced by 50% and heat recovery is used in a forced ventilation system. For this variant the summer season was not taken into account.

Table 12. Maximum and minimum indices of annual energy demand for heating.
The analysis of the impact of reducing the ventilation air flow rate by 50% and using heat recovery in a forced ventilation system (variables: location, heat capacity, air change rate, thermal performance standard)

| | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 240.00 | 199.99 | 196.60 | 203.65 | 224.29 | 262.32 | 262.09 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 27.23 | 18.61 | 18.53 | 18.86 | 25.38 | 34.82 | 26.49 |
| $\Delta_h$ [%] | 11.35 | 9.31 | 9.43 | 9.26 | 11.32 | 13.27 | 10.11 |

In all the locations maximum values of the index occur for the maximum ventilation air flow rate (4.0 $h^{-1}$) and the highest internal heat capacity (F), while minimum values were found for the minimum ventilation air flow rate (0.5 $h^{-1}$) and the highest internal heat capacity (F). Therefore, it is possible to achieve a reduction in energy demand for heating by about 20% for buildings with low thermal performance and a low air change rate to about 70%.

Table 13 lists extreme values of energy demand indices when all the above-mentioned thermal upgrading means are applied. The summer season was not taken into account.

Table 13. Maximum and minimum indices of annual energy demand for heating and cooling.
The analysis of the impact of all the standard means of thermal upgrading considered in the paper (variables: location, heat capacity, air change rate, thermal performance standard)

| | Chojnice | Gdańsk | Legnica | Nowy Sącz | Przemyśl | Suwałki | Zakopane |
|---|---|---|---|---|---|---|---|
| MAX $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 242.61 | 203.83 | 199.95 | 207.88 | 227.80 | 264.12 | 267.22 |
| MIN $EU_h$ [kWh $a^{-1}$ $m^{-2}$] | 28.10 | 19.71 | 20.07 | 20.60 | 26.73 | 35.77 | 28.28 |
| $\Delta_h$ [%] | 11.58 | 9.67 | 10.04 | 9.91 | 11.73 | 13.54 | 10.58 |
| MAX $EU_c$ | 15.47 | 19.24 | 21.61 | 22.82 | 24.06 | 17.81 | 14.17 |
| MIN $EU_c$ | 0.37 | 0.47 | 3.28 | 2.40 | 1.84 | 0.73 | 0.00 |
| $\Delta_c$ [%] | 2.39 | 2.44 | 15.18 | 10.52 | 7.65 | 4.10 | 0.00 |

The highest values of the index of effective energy demand for heating occur for buildings with low thermal performance (1982), very low heat capacity (A), and the maximum air change rate (4.0 $h^{-1}$). The lowest values of the index of effective energy demand for heating were found for buildings with high thermal performance (2017), ultra high heat capacity (F), and the minimum air change rate (0.5 $h^{-1}$). By applying the thermal upgrading means considered above, about 80% energy savings can be achieved over the "1982" building standard.

As for effective energy for cooling, the reduction in energy demand for cooling can be as much as 45%.

## Conclusions

The method based on a simulation using a lumped-parameter model enables a simplified study of the impact of time–varying building occupancy conditions.

A possible reduction in the effective energy demand for heating and cooling with the aid of standard means of thermal upgrading was studied in the paper. This is, however, a simplified analysis, since it fails to consider power required by a forced ventilation system or an electric drive of exterior blinds.

In Poland's climatic conditions constructing buildings with high internal heat capacity is advisable. This allows to reduce the effective heat demand for both heating and cooling. The index of energy demand for heating is many times larger than the index of energy demand for cooling.

Improving thermal performance of the envelope obviously translates into a lower index of annual energy demand for heating (by about 10% at the maximum). As for buildings with very low heat capacity, however, such an improvement can result in a rise in energy demand for cooling.

The higher the requirements concerning thermal performance are, the higher the index of the annual effective energy demand for cooling becomes. This is a consequence of the fact that heat losses by transmission are lower so the rate of removing heat gains from a building is reduced. It is particularly evident in the case of a building with low internal heat capacity.

With a minimum glazed surface area of the envelope that is required by law, using exterior blinds at night-time has only a little impact on reducing the $EU_h$ index (by up to 3.3%), while in summer the blinds considerably decrease the effective energy demand for cooling (even up to 39%).

Reducing the ventilation air flow rate when occupants are absent provides substantial power savings in winter. In summer, however, the results depend on heat gains in a building and the outdoor air temperature. Hence, a conclusion may be drawn that these factors should be also taken into account in an algorithm used to control a ventilation system featuring a periodically variable air flow rate.

Increasing the ventilation air flow rate (the air change rate) leads to a rise in energy demand for heating, but in summer it allows the removal of excess heat from a building. On the other hand, reducing the ventilation air flow rate in buildings results in increasing energy demand for cooling and extending the cooling period.

Using recuperation in winter has the effect of improving energy efficiency, while in the cooling period it causes a rise in energy demand for cooling.

In Polish climatic conditions standard means of thermal upgrading allow the energy performance of existing buildings to comply with more stringent requirements.

Further improvement of energy efficiency can be achieved by using renewable energy sources or using waste heat, e.g. from cooling equipment, for hot water preparation (Rusowicz *et al.* 2014).

## References

Grzebielec, A.; Rusowicz, A.; Ruciński, A. 2014. Analysis of the performance of the rotary heat exchanger in the real ventilation systems, in *9th International Conference. Environmental Engineering,* 22–23 May 2014, Vilnius, Lithuania.

MI. 2002. *Regulation of the Minister of Infrastructure of 12 April 2002 on technical specifications for buildings and their location* (Journal of Laws of 2015, item 1422, consolidated text) (in Polish).

MIC. 2017. *Typical statistical climate data for the Polish area for building energy performance purposes* (in Polish). Ministry of Infrastructure and Construction [online], [cited 15 January 2017]. Avaible from Internet: http://www.mib.gov.pl/2-Wskazniki_emisji_wartosci_opalowe_paliwa.htm

MID. 2015. Regulation of the Minister of Infrastructure and Development of 17 July 2015 on the methodology for calculating the energy performance of buildings and dwelling or building which is part of the whole technical self-utility, and the preparation and presentation of certificates of energy performance (Journal of Laws of 2015, item 1422) (in Polish).

*PN-B-02020:1982 Thermal protection of buildings – Requirements and calculations* (in Polish).

*PN-B-02020:1991 Thermal protection of buildings – Requirements and calculations* (in Polish).

*PN-EN ISO 10077-1:2006 Thermal performance of windows, doors and shutters – Calculation of thermal transmittance* – Part 1: General.

*PN-EN ISO 13790:2009 Energy performance of buildings – Calculation of energy use for space heating and cooling.*

Rusowicz, A.; Grzebielec, A.; Ruciński, A. 2014: Energy conservation in buildings using refrigeration units, in *9th International Conference. Environmental Engineering,* 22–23 May 2014, Vilnius, Lithuania.