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Limiting thermal energy requirements and the development of standards for the energy-efficiency of residential buildings in Belarus

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ABSTRACT

This paper discusses the prospects and directions of development of energy-efficient construction in Minsk, Belarus. A solution to the issue of the limiting heat and energy performance of buildings to which one should strive is proposed. The concept of a building with "limiting heat and energy performance" is introduced. In such a building the heat transfer resistance of the building envelope and the degree of tightness are chosen in such a way that the transmission heat loss and infiltration heat loss resulting from incomplete building tightness and imperfect heat transfer is equal to the total value of the energy of household heat and solar energy. The calculations of the "limiting" heat energy performance for the climatic conditions of the city of Minsk are given. The materials presented in the article can be used in the development of standards and in the design of energy-efficient buildings.

Keywords:
Thermal Performance; Buildings; Infiltration; Insulation; Belarus

1. Introduction

Energy saving, during the operation of buildings, is one of the main directions of development of construction. In developed countries buildings account for more than 70% of the generated electricity and 40% of primary energy consumption, as well as 40% of CO_2 emissions from combustion [1]. The analysis of the regulatory framework of the countries of the world community regarding the energy performance of buildings showed that the vector of development of standards is aimed at increasing their energy efficiency [2]. The most powerful lever for managing the energy performance of buildings is the country's regulatory framework. In the EU countries the energy efficiency of buildings is governed by basic documents, the EU directives on energy efficiency of buildings [3, 4] and the EU directive on energy efficiency [5]. At present the requirements of directives [3] and [4] have basically been fulfilled and a new directive [5] has been adopted that clarifies the tasks set in [3] and [4] and outlines directions for the development of energy efficiency up to 2050. The mentioned documents [3-5] outlined target development indicators, such as a reduction in greenhouse gas emissions by at least 20% below the level in 1990, and a 20% reduction in energy consumption by 2020 in the European Union.

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The terminology used by the EU and CIS countries contains various definitions for buildings with high energy efficiency indicators [2,6], which are included in national roadmaps as a target for future new buildings. In all countries the requirements for thermal resistance and tightness of external building envelopes are consistently increasing [2,6,7], heat supply systems and renewable energy sources are used in building energy supply systems.

Currently a significant number of buildings that comply with the “passive house” standard [8], as well as houses with “zero energy consumption” and “active buildings” have already been built and are in operation [9,10].

According to the definitions given in [11] a house with zero energy consumption, also a zero-energy building (German “Nullenergiehaus”) is a building with high energy efficiency, capable of generating energy from renewable sources on site and consuming it in equal quantity throughout the year. An active house (“energy plus house”), also a house with a positive energy balance, a house according to the standard “energy plus” is a building that produces energy for own needs more than in sufficient quantities. The total annual energy consumption is negative in comparison with the low energy house. It follows from the definition that the concepts of zero-energy or energy plus house characterize primarily the energy supply system of a building, but not its heat and energy indicators. These buildings with their heat and energy indicators as a rule significantly exceed the requirements of effective standards in these countries. At the same time mass construction is carried out on the basis of these standards.

The results of a study [12] of the dependence of regulatory requirements on the thermal performance of building envelopes on climatic conditions for operation in different countries showed that these conditions have little effect on the heat transfer resistance of fences. More significant is the impact of economic indicators [3]. In the economic approach, thermal protection standards are selected from the point of view of equilibrium of investments and energy costs saved during the life cycle. Here the problem remains the prediction of changes in the cost of energy during the life cycle of the building. The question arises: how to find the boundary conditions for normalizing the heat and energy performance of buildings, what to stop, which is the focus of this paper.

2. Limiting Thermal Energy Requirements of Residential Buildings in Belarus

By considering the directions of the development of construction, it is important to solve the problem of the limiting heat and energy performance of buildings. Simplistically, it is possible to determine the necessary building heat demand for heating as the difference between the heat loss and the energy of the heat entering the building. Thermal losses of buildings, the returnable and irrecoverable losses of thermal energy are usually not shared. Transmission losses of thermal energy through the building envelope and the infiltration heat loss due to heating the air entering the building through the leaks of the external building envelope are fundamentally irreversible. Fundamentally recoverable are the losses of thermal energy with exhaust air when using forced mechanical ventilation with the recovery of thermal energy. The use of highly efficient heat exchangers can provide almost 100% return of the heat energy of the exhaust air. The non-ideal heat exchanger increases the energy of irrevocable heat loss from the building.

It is advisable to create building projects with the possibility of increasing the energy efficiency class during the life cycle as energy-efficient technologies develop and economic feasibility [13]. With this approach the initial project should pay particular attention to the insulation and sealing of the shell of buildings so as not to return to this issue in the future. In this case a reduction in thermal energy consumption during operation will be achieved by efficient utilization of the secondary energy resources of the building without the need for additional work to warm and seal the outer shell of the building. To do this the building project must provide for the possibility of installing additional engineering systems at the stage of its operation.

To implement the proposed design principles already today, regulatory requirements for thermal performance and tightness of enclosing structures should be ahead of economic and technical feasibility from the perspective of the “current moment”. Such a statement of the problem actualizes the question of the approach to the selection of the "limiting" heat energy indicators of modern buildings.

Based on the formulated principles, the condition of a sufficient degree of insulation and sealing of the building envelope can be fulfilled if the transmission heat loss through the building envelope plus infiltration heat loss resulting from incomplete tightness of buildings and imperfect heat transfer is equal to the average heat input to the building during the heating season as shown in Eq. (1).

$$(T_{in} - T_{out})(K_{tr} + K_{inf}) = q_{in} + q_{sol} \quad (1)$$

where, K_{tr} – the heat transfer coefficient through the external building envelope, reduced to 1m^2 of the heated area of the building, Wm^{-2}K^{-1}, and is determined by the Eq. (2).

$$K_{tr}=1/S_0*\Sigma(S_i/R_i) \quad (2)$$

where, S_0 is heated area of the building, S_i area in m^2, and R_i is reduced heat transfer resistance of the i external building envelope, m^{2}KW^{-1}.

However, T_{in} and T_{out} are the average temperature in the building for the heating season and the outdoor temperature respectively ° C. K_{inf} – radiation heat transfer reduced to 1 m^2 of the heated area of the building, Wm^{-2}K^{-1}, is determined by the Eq. (3) and Eq. (4).

$$K_{inf} = 1/3600 * \rho c(V_{inf} + (1 - \eta)V_b) \quad (3)$$

$$V_{inf} = \varepsilon * n_{50} * V_b \quad (4)$$

where, η is energy efficiency coefficient of the utilizer in the ventilation system; n_{50} is air exchange in a building with a differential pressure 50Pa, [14], 1/h; ε is location dependent coefficient [15]; V_b is heated volume of the building m^3; ρ *in* kgm^{-3} and c in Jkg^{-1}K^{-1} are average values for the heating season air density and heat capacity respectively. q_{in} and q_{sol} are average values for the heating season for the power of domestic heat and solar radiation entering the building, respectively, Wm^{-2} of the heated area.

Household heat and solar energy entering the building can be considered as constants depending on the climatic conditions of functioning and population of the building. To fulfill equality, the values of K_{tr}иK_{inf} are controlled, providing during design and construction the necessary values of R_i, n_{inf}.

The reduced resistance to heat transfer of enclosing structures, Ri depends not only on the thickness of the insulation layer, but also on their heat engineering homogeneity. Therefore, the optimization of the thermal performance of the external walls must be performed using detailed calculation methods [16].

By increasing the degree of tightness of the building and the efficiency of the heat exchanger in the ventilation system, decreasing the value of n_{inf}, it is possible to weaken the requirements for transmission heat losses, reduce the degree of insulation of the building, and vice versa. The proposed design approach makes it possible to optimize construction costs. A building can be constructed using a natural-inspired ventilation system. Already at the operation stage a controlled mechanical supply and exhaust ventilation system with heat energy recovery can be installed.

The heating system of a building that satisfies the conditions stated above is necessary for periods of the heating season when the outdoor temperature drops below average. We will call such buildings a building with “limiting thermal performance”.

The specific energy Q_{sum}, kWhm^{-2} necessary to compensate for heat losses during these periods is equal to Eq. (5).

$$Q_{sum} = 0{,}024 \cdot \sum_{i=1}^{I}(q_{ip} + q_i) \cdot \tau_i \tag{5}$$

where q_i – additional specific power in the forced ventilation system with the recuperation of thermal energy of the removed air, necessary to ensure the operation of the heat exchanger at low temperatures, Wm^{-2}. q_{ip} is additional specific power in the heating system at each interval calculated to be from Eq. (6).

$$q_{ip} = f_1 \Delta T_i \tag{6}$$

where, f_1 is specific heat loss coefficient of the building [13], Wm^{-2}K^{-1}, including transmission and infiltration heat losses and equal under the assumptions made om Eq. (7).

$$f_1 = \frac{q_{in} + q_{sol}}{\Delta T_0} \tag{7}$$

where, τ_i is the duration of the time interval with the temperature T_i, days. $\Delta T_i = T_m - T_i$; $\Delta T_0 = T_0 - T_m$; $T_0 = 20$°C *which is the* average air temperature in the building, °C; T_m is average outdoor air temperature during the heating season, °C; T_i - outdoor temperature on the ith interval, °C.

Table 1 presents the durations of the intervals taken from [17], in which the outdoor temperature drops below the average value for the heating season and the additional energy that is required for heating during these periods. For example, the data are taken for the city of Minsk.

Table 1
Intervals of temperatures and their duration and values of additional energy, q_{ip}

T_i T_{i+1},°C	-29,9 - 25,0	-24,9 - 20,0	-19,9..-15,0	-14,0 - 10,0	-9,9 -5,0	- 4,9 0	$\sum_{1}^{I} q_{ip}$
τ_i, days	0,2	1,0	3,8	11,6	27,4	51,9	
q_{ip},kWh /m^2	0,042	0,171	0,500	1,066	1,436	0,6	3,87

At low outdoor temperatures the air condenses in the exhaust duct of the heat exchanger and then freezes moisture, which leads to its destruction. To ensure the operation of the heat exchanger at low temperatures, the most common method is to heat the outdoor air in the supply duct to the boundary of the operating temperature range [18]. In this case additional energy is needed to heat the supply air equal to Eq. (8).

$$Q_I = 0{,}024 \cdot \sum_{i=1}^{I} q_i \cdot \tau_i \tag{8}$$

where, $q_i = \Delta T_{i1} \cdot V_0 \cdot \rho_l \cdot c_l$; $\Delta T_{i1} = T_{01} - T_i$; T_{01} is lower limit of the operating temperature range of the heat exchanger; c_l – specific heat of air, $Jkg^{-1}K^{-1}$; V_0 is air exchange volume in m^3s^{-1}; and P_l is air density.

When using the method of operation proposed in [19], controlled freezing of the heat exchanger with subsequent defrosting is allowed. In this case the efficiency of the heat exchanger does not decrease. Additional energy is spent only on melting ice and will be equal to Eq. (9).

$$Q_l = 0{,}024 \cdot \sum_{i=1}^{l} q_{it} \cdot \tau_i \tag{9}$$

where, $q_{it} = m_i \cdot c_l$; W; $m_i = V_0*(\rho_l - \rho_i)$; in the case when the exhaust air moves vertically downward, coinciding with the direction of movement of condensed moisture, kg; c_l is heat of the ice-water phase transition, kJ/kg; τ_i is duration of the i^th^ interval; ρ_l, ρ_i - water vapor density in the air of the building premises and at the temperature of the i^{th} interval, respectively.

When exhaust air moves against the direction of condensed moisture, $m_i = V_0*(\rho_0 - \rho_i)$. Where, ρ_0 water vapor density in air at temperature 0°C.

Table 2 presents the results of calculations of the additional energy necessary to ensure the operation of the building's ventilation systems at low outdoor temperatures. The q_i values in Table 3 correspond to the case of outdoor air heating in the supply duct. The values of Q_{it}, and Q_{it1} are calculated for the case when partial freezing of the heat exchanger is allowed when the air moves in the direction and against the direction of the condensate drain, respectively.

Table 2

Conditions and results of calculations of additional energy for each temperature range

Air exchange rate: V_l =1,5 $m^3/(m^2*h)$; ρ_l=0,0069kg/m^3								
T_i, °C	27,45	22,5	17,5	12,5	7,5	2,5	Q_l, kWh/m^2	Q_{sum} kWh/m^2
Q_i kWh/m^2	0,1059	0,4179	1,159	2,227	2,166	0	6,08	9,95
Q_{it}, kWh/m^2	0,0012	0,0043	0,011	0,0203	0,034	0	0,071	3,94
Q_{it1}, kWh/m^2	0,0006	0,0019	0,0034	0,0023	0	0	0,008	3,88

From the data given in the Table 2, the following results can be drawn.

- The most energy-intensive way of operating the heat exchanger when heating the supply air. The energy consumption for its heating exceeds the additional transmission heat loss.
- An order of magnitude smaller losses during operation of the heat exchanger in the partial freezing mode followed by defrosting of ice when the exhaust air moves in the direction of condensate drain. The whole condensed moisture enters the freezing zone.
- The most favorable mode of operation when the exhaust air moves against the condensate drain. In this case only that part of the moisture that falls out in the heat exchanger in the freezing temperature area freezes.
- Specific heat energy consumption for the heating season for the conditions of the city of Minsk with the optimal operating mode of the heat exchanger will be no more than 4 kWh/m^2 for the heating season.

The presented results do not take into account the electrical energy necessary for the operation of the fans in the ventilation system of the building. The experience of operating energy-efficient buildings in the Republic of Belarus showed [13] that when apartment-type ventilation systems are used in in high-rise buildings, about 0,5 W/m^2 of the heated building area or 4,5 kWh/m^2 per year is used for fans.

3. Case Study: 10-Storey Energy-Efficient Building

Let's consider the calculation of the limiting heat and energy indicators at the example of an apartment building. Table 3 presents the main indicators of a 10-story energy-efficient building, taken as input to the calculation of heat and energy indicators. The values of resistance to heat transfer of the external enclosing structures are taken equal to the regulatory requirements [16]. The building is supposed to use a forced ventilation system with efficient heat recovery. High tightness of the shell is ensured that meets the requirements for energy-efficient buildings [20]. Air exchange due to air infiltration through the shell was calculated in accordance with [15]. Table 4 presents the main indicators of the building and the conditions adopted in the calculations. Table 5 presents the estimated heat and energy performance of the building. The following notations are accepted:

S_1, S_2, S_3, S_4, – the area of external walls, ceilings above the basement, coverings of the upper floor, windows, respectively, m^2;

R_1, R_2, R_3, R_4 – reduced resistance to heat transfer of external walls, ceilings above the basement, covering the upper floor, windows, respectively, m^{2}KW^{-1};

S_h - heated area of the building, m^2;

η- heat exchanger efficiency in a building ventilation system;

V_n, - air exchange level adopted in accordance with [21], m^3/h;

V_b – heated volume of the building, m^3;

q_{s1}, q_{s2} - solar radiation power, in accordance with [22], for the meridional and latitudinal location of the building, respectively, Wm^{-2};

$$q_{vi} = \frac{\Delta T_0 S_i}{R_i \cdot S_h} \tag{10}$$

q_{vi}- average specific heat loss rate in the heating season through the corresponding enclosing structures, Wm^{-2};

$$q_l = \frac{(\mathrm{V_n}(1-\eta)+\mathrm{V_{inf}})\rho \cdot c \cdot \Delta \mathrm{T_0} \cdot}{3600 \cdot S_h} \tag{11}$$

q_l - average specific heat loss rate with air exchange in the heating season, Wm^{-2}.

Table 3
The main indicators of the building and the conditions adopted in the calculations

S_1, m^2 / R_1 m^{2}K/W	S_2, m^2 / R_2 m^{2}K/W	S_3, m^2 / R_3 m^{2}K/W	S_4, m^2 / R_4 m^{2}K/W	n_{50}, 1/h	n_{inf}, 1/h	V_b m^3	η_{rec}	V_n, m^{3}hч	T_{out} °C	S_h, m^2
520 / 3,2	1500 / 1,8	1500 / 6	1104 / 1,0	0,6	0.042	4,5*10^4	0,95	22500	-0,9	15000

Table 4
Estimated heat and power indicators of the building

q_{v1}, W/m^2	q_{v2}, W/m^2	q_{v3}, W/m^2	q_{v4}, W/m^2	q_l W/m^2	q_v, W/m^2	q_{in} W/m^2	q_s W/m^2	q_{in} +q_s, W/m^2
2,40	0,60	0,35	1,54	1,51	6,63	6,15	1,5	7,65/

From the calculation results shown in Table 5, we can conclude that for the considered high-rise building, the standard values for the heat transfer resistance of building envelopes accepted in the country are limiting, i.e. there is no point in increasing them. For the building the condition stated above is fulfilled: the power of the sum of the transmission heat loss, the infiltration heat loss resulting from the incomplete tightness of the buildings and the heat loss resulting from the imperfect heat exchanger are less than the sum of the power of domestic heat and solar energy.

It should be noted that the limiting heat and energy performance of buildings will depend on the compactness and climatic conditions of operation. Table 5 presents the limiting values of the reduced heat transfer resistance for buildings with different indicators of compactness. For intermediate compactness indicators the values of R_i will turn out to be less than the given values. From the data given in the table, it can be concluded that, for buildings of 3 floors or more, the heat transfer resistance is in a technically feasible range of values. For the case of a 2-story building, the implementation of a heat transfer resistance value of 20 m^{2}K/W will require a thermal insulation layer of at least 80 cm, which makes it difficult to implement a building envelope. Therefore, the possibility of increasing the energy efficiency of buildings with low compactness should be realized by the wider use of renewable energy sources.

Table 5
Limit values of reduced heat transfer resistance

Comp, 1/m	N	R_{st}, m^{2}K/W	R_{per}, m^{2}K/W	R_{pokr}, m^{2}K/W	R_{ok}, m^{2}K/W	q_v, m^{2}K/W
0,22	10	3,2	2,5	6	1,0	6,63
0,44	3	5	3,5	8	1,2	7,48
0,69	2	20	12	20	1,4	7,32

To focus on the degree of tightness of the building envelope. Like transmission infiltration heat loss is irreversible. To maintain the overall level of heat loss while reducing the tightness of the building, it is necessary to increase the heat transfer resistance of the building envelope. Let us consider the building, the indicators of which are given in Tables 3 and 4.

Let us increase the air permeability of the building from n_{50}=0,5, which corresponds to the requirements adopted for passive buildings [20], to n_{50}=1,5, which corresponds to national standards for this type of building [23]. Free air exchange in a multi-story building will change, in accordance with [15], from the level of n_{inf}=0,15 1/h to the value of n_{inf}=0,06 1/hour. At the same time, the power of the infiltration heat loss will increase by Eq. (12).

$$q_{inf} = \frac{h}{3600}(n_{inf1} - n_{inf2}) \cdot \Delta T \cdot c \cdot \rho, \tag{12}$$

where h=2,5 m which is accepted floor height; and ΔT_0 = 20,9°C.

For the accepted assumptions, we obtain an increase in the power of infiltration heat loss equal to q_{inf}=1,74 Wm^{-2}.

To compensate for the increase in infiltration heat loss, the heat transfer resistance of the external walls must be increased to as per Eq. (13).

$$R_{1izm} = R_1/(1 - S_h \cdot \Delta q/(S_1 \cdot \Delta T) \tag{13}$$

For R_1=3,2 m^2K/W we get R_{1izm}=4,1 m^2K/W.

Considering the fact that to increase the resistance to heat transfer, additional insulation of the building is necessary, and the tightness is achieved mainly by the quality of construction work, the economic feasibility of increasing the tightness of buildings becomes extremely clear. The question of the ultimate value of tightness remains open. It occurs when you turn off the mechanical supply and exhaust ventilation system in the building. In this case, it is necessary to proceed to airing the rooms through the windows. If the windows are closed, air infiltration should provide the minimum necessary air exchange for breathing.

As an extreme case you can consider a completely airtight building without air outside with a closed air exchange system with the absorption of carbon dioxide, water vapor, etc.

4. Conclusions

In all countries the requirements for thermal resistance and tightness of external building envelopes are increasing, heat supply systems and renewable energy sources are used in building energy supply systems. The terminology used by EU and CIS countries contains various definitions for buildings with high energy efficiency indicators, which are included in national roadmaps as a goal for future new buildings. At the same time there is a lack of understanding of which heat and power indicators should be sought for in the development of regulatory documents and design. This paper proposed a solution to the issue of limiting heat and energy performance of buildings. The concept of a building with "limiting heat and energy performance" is introduced. In such a building, the heat transfer resistance of the building envelope and the degree of tightness are chosen in such a way that the transmission heat loss and the infiltration heat loss resulting from incomplete building tightness and imperfect heat transfer are equal to the total value of the energy of household heat and solar energy. If the building with the limiting heat and energy performances is equipped with forced ventilation with an effective system for utilizing the heat energy of the exhaust air, we will obtain zero energy demand for heating for average operating conditions. Limit values depend on the compactness of buildings and climatic conditions of use. Calculations of the "limiting" heat energy performances for the climatic conditions of the city of Minsk are given, which showed that for high-rise buildings the current regulatory requirements for the reduced heat transfer resistance of building envelopes satisfy the formulated "limit" condition, while for buildings with a low number of storeys, the values of the heat transfer resistance of the building designs should be increased. The article emphasizes that infiltration and transmission heat losses are irreversible and are equivalent in their effect to their level. Taking into account, that to increase the resistance to heat transfer, additional insulation of the building is necessary, and the tightness is achieved mainly by the quality of construction work, the economic feasibility of increasing the tightness of buildings becomes extremely clear. The question of the limit value of tightness remains open. The materials presented in the article can be used in the development of standards and in the design of energy-efficient buildings.

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