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ENERGY CONSERVATION, NEW, AND RENEWABLE ENERGY SOURCES

The Optimum Levels of the Thermal Protection of Residential Buildings under Climatic Conditions of Russia

S. P. Filippov, M. D. Dil'man, and M. S. Ionov

Institute of Energy Research, Russian Academy of Sciences, ul. Nagornaya 31, bldg. 2, Moscow, 117186 Russia

Abstract—The present paper reports the results of determining the optimum values of the resistance of building envelopes to heat transfer for both existing and newly constructed buildings for regions of Russia with different climatic conditions. An analysis for the sensitivity of obtained optimum solutions to changes in external factors has been made. The potential of energy saving in both the existing housing stock and in newly constructed buildings due to the improvement of thermal protection performance of buildings to the optimum level has been determined.

Keywords: heat supply, space heating, resistance to heat transfer, building envelopes, thermal protection, energy saving potential

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The housing sector is one of the largest consumers of fuel-and-energy resources. In 2011, for space heating and hot water supply (HWS) of residential buildings, 2063 million GJ of thermal energy were used, which comes to 37.5% of its total generation in the country. Besides, for heat supply of low-rise housing development in 2011 there were consumed 2019 million GJ of thermal energy produced by firing various types of fuel, mainly natural gas (1486 million GJ), as well as coal (293 million GJ) and firewood (237 million GJ). Over the past years in the structure of heat consumption by the housing sector the share of space heating has been increased steadily, which by the year 2011, reached 73.7% in the country as a whole. The HWS accounts for the remaining 26.3%. This tendency was mainly determined by the more tight control for hot water consumption by households as a result of mass installation of appropriate metering devices with the small scope of carrying out energy saving measures intended to reduce heat losses in buildings. Thermal energy consumption for the HWS is mainly determined by the size of population, habits, and living standards of people, while for space heating, by the total floor area of the housing stock, the thermotechnical performance of building envelopes, the sanitary and hygienic code (the standard air change rate), and climatic parameters of a region in which a dwelling is located.

According to data provided by the Rosstat (Federal Service of State Statistics), the total floor area of the housing stock in the Russian Federation as of the end of the year 2012 was about 3.3 billion m^2, of which 72.2% were related to urban development. Dilapidated and unsafe dwellings account for 3% of the existing housing stock. Construction of new residential buildings for the period from 2000 to 2012 increased by a factor of more than 2—from 30.3 to 65.3 million m^2 per year. The share of low-rise apartment buildings in the new housing construction during the given period was, on the average, from 41 to 44% of annually commissioned dwelling space. According to forecasts made by specialists of the Institute of Energy Research, Russian Academy of Sciences, by the year 2030, the housing stock in Russia might increase to 4.8 billion m^2, i.e., by a factor of almost 1.5.

A characteristic feature of the existing housing stock is a large share of energy-wasteful buildings constructed in accordance with the requirements contained in the building codes (SNiP) that were adopted in 1979 [1] and before. In these documents there were established low standard values of the resistance of building envelopes to heat transfer, which was caused by the low cost of energy in the USSR at that time and a shortage of construction materials. The share of such buildings in the structure of the existing housing stock exceeds 80%. After 2003, construction has been carried out according to the requirements of SNiP 23-02-2003 "Thermal Performance of the Buildings" [2] in which the standards for thermal protection of buildings were made much more stringent. In [2] the standardized values of the resistance of residential building envelopes to heat transfer are given according to the number of heating degree-days (HDDs) in the area where construction is carried out. Table 1 gives the numerical values of these requirements as applied to the capital cities of all eight federal districts and for

Table 1. Normative values of the resistance of envelopes of residential buildings to heat transfer for capital cities of federal districts (m^2 K)/W

City	Type of a building envelope			
	walls	windows and glazed balcony doors	ceilings and floors	
			basement ceilings	attic floors
Moscow	3.13/0.92	0.52/0.38	4.12/2.07	4.12/1.38
St. Petersburg	3.08/0.88	0.51/0.38	4.06/1.98	4.06/1.32
Rostov-on-Don	2.63/0.8	0.41/0.34	3.49/1.81	3.49/1.21
Pyatigorsk	2.61/0.77	0.41/0.34	3.46/1.72	3.46/1.15
Nizhni Novgorod	3.21/0.98	0.54/0.52	4.23/2.2	4.23/1.47
Yekaterinburg	3.49/1.05	0.60/0.52	4.59/2.37	4.59/1.58
Novosibirsk	3.71/1.13	0.63/0.52	4.87/2.54	4.87/1.70
Khabarovsk	3.56/0.98	0.61/0.52	4.68/2.20	4.68/1.47

Note: In the numerator the normatives now in force are given [2], while in the denominator, the requirements contained in the previous normative document [1].

Table 2. Climatic data for the heating season in selected cities

City	t_{out}, °C*	The characteristics of the heating season		Wind velocity in January, m/s	HDD, °C day/yr
		Duration, day/yr	Mean air temperature, °C		
Moscow	–28	214	–3.1	4.9	4943
St. Petersburg	–26	220	–1.8	4.2	4796
Rostov-on-Don	–22	171	–0.6	6.5	3523
Pyatigorsk	–20	175	0.2	6.3	3465
Nizhni Novgorod	–31	215	–4.1	3.7	5182
Yekaterinburg	–35	230	–6.0	5.0	5980
Novosibirsk	–39	230	–8.7	5.7	6601
Khabarovsk	–31	211	–9.3	5.9	6182

* The ambient air design temperature used for designing heating systems.

Russia as a whole, and these values have been calculated according to the recommendations [1–4] at a standardized value of the room temperature 20°C [3]. Climatic data for these cities related to the heating season (the cold season with mean daily temperature of the ambient air no higher than + 8°C) are presented in Table 2. On the average, in Russia the value of HDDs is about 5140°C day (Fig. 1).

It follows from Table 1 that over the past 30 years the requirements for the resistance of some types of building envelopes to heat transfer have been tightened by a factor of 2–4, except for transparent structures, with respect to which the tightening of requirements turned out to be minimum—by the factor of merely 1.1–1.4. Nevertheless, the standards for thermal protection of buildings that are valid in Russia still remain to be considerably lower (up to the factor of 2) than the similar standards adopted abroad in an effort to implement the energy-saving policy [5, 6], and even for milder climatic conditions (Fig. 3).

It should be noted that the methods of calculating the number of HDDs in Russia and abroad somewhat differ. In Russia the number of HDDs is determined on the basis of the standardized room temperature for the heating season, while abroad, for the entire period with the ambient air temperature lower than a certain value. These differences are due to the fact that abroad decentralized space heating systems, whereas in Russia, centralized heat supply systems, prevail. In order to compare the demands for heating in Russia and in foreign countries, it is possible to use information borrowed from the climatic database "NASA Surface Meteorology and Solar Energy" on annual degree-days of deviation from the level of +10°C in the direc-

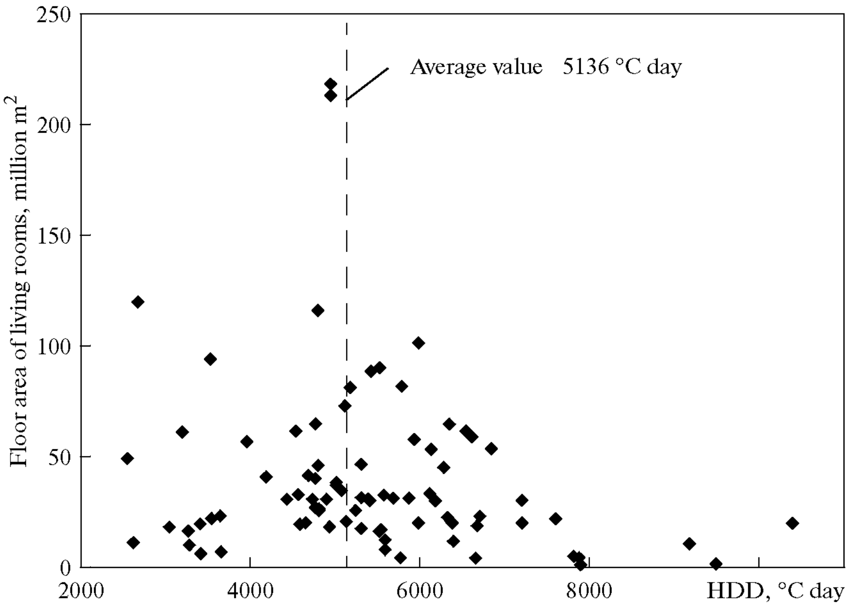

Fig. 1. Distribution of the housing stock in Russia by a value of HHD (averaged over the federal subjects as to the end of 2012).

tion of lower values—HDD10 (Arctic heating degree days below 10°C). For Russia and for capital cities of foreign countries the indicator HDD10 is (in °C day/yr): Moscow—2964, Saint-Petersburg—2750, Nizhni Novgorod—3122, Rostov-on-Don—1676, Yekaterinburg—3759, Novosibirsk—4115, Khabarovsk—4425, Helsinki (Finland)—2601, Oslo (Norway)—2324, Stockholm (Sweden)—1847, and Copenhagen (Denmark)—1311. The relationship between HDD0 and HDD18, respectively, degree-days of deviation from 0°C and +18°C, for Russia and for the countries mentioned above is also the same. Thus, on the largest part of the territory of Russia the demand for thermal energy needed for space heating is higher than in these European countries. Hence, in our country, the motivation for enhancing thermal protection of buildings should be stronger.

Today experts are discussing the new version of SNiP 23-02-2003 "Thermal Performance of the Buildings" harmonized with similar European normative documents [7]. However, in the new version the basic requirements for determining the values of the resistance of building envelopes to heat transfer remained, in fact, the same. Besides, now their adjustment in the direction of lower values is permitted when there is an appropriate economic substantiation. In this case, for each type of a building envelope, the lower limit of possible reduction given by an appropriate coefficient is fixed. For walls this coefficient is 0.63, for windows, 0.95, and for other structures, 0.8. Abuse of these possibilities is fraught with the return to construction of energy-wasteful buildings. Obviously, this would make the construction works less expensive and make new dwellings more affordable for people; however, with an anticipated growth of prices for energy carriers, the expenses for providing comfortable living conditions (space heating in winter and air conditioning in summer) in such buildings will inevitably increase.

Thus, the problems of determining optimum values of the resistance of building envelopes to heat transfer are urgent enough in regard to new housing development (the first problem) and to the existing housing stock (the second problem). The results of solving the first problem can find their application when elaborating new normative documents related to the thermal protection of buildings. Their importance is determined, on the one hand, by prolonged periods of the usage of newly constructed buildings (50–60 years and longer), with due regard for energy carriers rising in price, and, on the other hand, by large anticipated volumes of new housing development at a very limited ability of people being able to pay. Solving the second problem will make it possible to obtain objective appraisals of the energy saving potential in the existing housing stock and to make the proper choice of economically substantiated measures for its implementation.

As a criterion for determining an optimum level of thermal protection of both newly constructed and existing buildings, the authors used the maximum of the net discounted income (NDI) for the accounting period, obtained as a result of increasing the resistance of a building envelope of the *i*th type to heat transfer.

The net discounted income is related to the unit of the floor area of heated rooms, rubles/m^2:

$$D_i = \sum_{t=1}^{T_{\text{acc}}} (-K_{it} + \Delta S_{it}^q) \Big/ \left\{ A_{\text{o}} \prod_{\tau=1}^{t} \left[\left(1 + p_\tau^r/100\right) I_\tau^C \right] \right\},$$

where T_{acc} is the accounting period, years; K_{it} are specific capital expenditures for increasing the resistance of a building envelope of the ith type to heat transfer made in the year t ($t \in T_{\text{acc}}$), rubles/yr; ΔS_{it}^q is the annual saving of financial resources needed for purchasing thermal energy as a result of increasing the resistance of the building envelope of the ith type to heat transfer, rubles/(m^2 yr); p_τ^r is a real bank credit interest rate, %; I_τ^C is the annual consumer price index; and A_{h} is the total floor area of rooms to be heated, m^2.

Specific capital expenditures K_{it} were determined as:

$$K_{it} = \left[\left(R_i - R_i^0\right) K_{it}^{is} + K_{it}^m \right] F_i$$

or

$$K_{it} = \left[\left(R_i - R_i^0\right) K_{i0}^{is} + K_{i0}^m \right] F_i \prod_{\tau=1}^{t} I_\tau^K,$$

where R_i and R_i^0 are, respectively, design and normative resistance of a building envelope of the ith type to heat transfer, (m^2 K)/W (for buildings constructed before 2000 the value of R_i^0 corresponds to the requirements given in [1], while for buildings constructed later, to the requirements given in [2]); K_{i0}^{is} and K_{it}^{is} are specific capital expenditures for thermal insulating materials used for increasing the resistance of a building envelope of the ith type to heat transfer related to the unit of the surface area of building envelopes of the ith type, correspondingly, initial ones and those made in the year t, rubles/(m^2 K)/W; K_{i0}^m and K_{it}^m are specific expenditures for construction and installation works on heat insulation of the building envelope of the ith type related to the unit of its surface area, respectively, the initial ones and those made in the year t, rubles/m^2; F_i is the surface area of building envelopes of the ith type, m^2; I_τ^K is the annual deflator of industrial production.

The annual saving of financial resources needed for purchasing thermal energy is:

$$\Delta S_{it}^q = \Delta Q_{it} c_t^q = \Delta Q_{it} c_0^q \prod_{\tau=1}^{t} I_\tau^q,$$

where ΔQ_{it} is the annual thermal energy saving due to an increase in the resistance of the building envelope of the ith type to heat transfer, GJ/yr; c_0^q and c_t^q are thermal energy tariffs, respectively, the initial one and that in the tth year, rubles/GJ; and I_τ^q is the annual index of thermal energy tariffs.

The value of ΔQ_{it} was determined as:

$$\Delta Q_{it} = 3.6 \times 10^{-6} (P_i^0 - P_i) F_i h_t,$$

where P_i^0 and P_i are the normative maximum and the design heat flows through the unit of the area of the ith building envelope, W/m^2; and h_t is the number of hours of the usage of the maximum thermal load in the year t, h/yr.

The maximum heat flow through the unit of the area of the ith building envelope (at the design outdoor temperature t_{out} for designing the space heating system is:

$$P_i = (1/R_i)(t_{\text{in}} - t_{\text{out}})(1 + \beta_i) n_i,$$

where t_{in} is the standardized indoor air temperature, °C; β_i is the dimensionless coefficient that takes into account additional heat losses through the building envelope of the ith type due to infiltration, exfiltration, solar radiation, etc. [8]; n_i is the dimensionless coefficient that takes into account the position of the building envelope to the wind direction [1].

In the course of investigations optimum values of the resistance of main components of building envelopes were determined: walls, windows (including glazed balcony doors), basement ceilings (above the non-heated underfloor spaces and basements), and attic floors.

The real bank credit interest rate p^r was assumed to be the same during the entire accounting period and equal to 6%. Macroeconomic indices were taken in accordance with the topical long-term forecasts made by the Ministry of Economic Development of the Russian Federation (Table 4). For the calculations the following initial values of average thermal energy tariffs in the federal districts were used (rubles/GJ): Central—344, Northwestern—281, Southern—420, North-Caucasus—349, Volga—299, Urals—267, Siberian—225, and Far Eastern—403. The initial values of specific capital investments K_{i0}^{is} were taken to be the same for all regions and equal to 140 rubles/(m^2 K)/W for walls, basement ceilings and attic floors, and 2000 rubles/(m^2 K)/W for windows. Expenses for construction-and-installation works K_{i0}^m were modeled by means of the function of the form $K_{i0}^m = a_i(R_i - R_i^0)^{1/m_i}$. The coefficients a_i and m_i were determined by means of processing the data on market cost of construction-and-installation works on heat insulation of building envelopes of the ith type at various values of R_i ($m_i > 1$). As a result, the coefficients were: for walls $a = 2076$, $m = 7.73$; for windows $a = 4216$, $m = 18.95$; for attics $a = 595$, $m = 17.54$; and for floors $a = 510$, $m = 18.38$.

In the course of investigations the effect of the geometric characteristics of buildings with a various number of stories on heat losses was taken into consider-

Table 3. Requirements on the resistance of building envelopes to heat transfer for new buildings constructed abroad, (m^2 K)/W

Country	Type of a building envelope			
	walls	windows	ceilings and floors	
			basement ceilings	attic floors
Great Britain	2.86	0.45–0.5	4.0	4.0–6.3
Germany	4.2	0.8	No data	4.2–5.0
The Netherlands	3.3–5.0	0.4–0.7	3.3–5.0	2.5–5.0
Denmark	3.3–5.0	0.7–1.0	5.0–10.0	5.0–10.0
Canada	3.3–5.6	0.5	4.4–4.7	4.9–5.2
Norway	5.6	0.8	No data	7.7
The USA	0.9–3.1	0.15–0.5	2.8–6.3	5.0–6.8
Finland	4.0	0.7	5.0	6.3
Sweden	5.0–10.0	0.7–1.0	5.0–10.0	5.0–10.0

Table 4. Annual macroeconomic indices averaged over the period

Macroeconomic indices	2012–2015	2016–2020	2021–2025	2026–2030	After 2030
Consumer price indices	1.053	1.046	1.036	1.031	1.030
Indices of prices for thermal energy	1.094	1.960	1.067	1.045	1.043
Deflators of the industrial production	1.051	1.680	1.047	1.027	1.024

ation. In this case the most important of these characteristics were the following:

—the ratio between the surface area of building envelopes (F_i) and the total floor area of its heated rooms (A_h), i.e., $k_i^F = F_i/A_\text{h}$;

—the structure of the surface areas of the building envelopes, because they have different values of the resistance to heat transfer, i.e., $\omega_i = = F_i/\sum_i F_i$.

It follows from Figs. 2 and 3 that the effect of the geometric parameters (k_i^F and ω_i) on the thermal performance of individual low-rise buildings (one–three stories) and multi-storied apartment buildings (4–25 stories) differ essentially. In low-rise buildings from 3.3 m^2 (one-storied building) to 1.7 m^2 (three-storied building) of total building envelopes are for 1 m^2 of heated rooms (see Fig. 2). For multi-storied buildings this ratio is considerably less and varies from 1.3 m^2 (four-storied) to 0.6 m^2 (25 stories). In this case, at the number of stories more than nine the changes in the coefficient k^F become insignificant. In the structure of surface areas of building envelopes, with the change-over from one-storied to three-storied buildings, the share of walls increases roughly from 35 to 52%, and that of windows, from 5 to 8%, while the total contribution of basement ceilings and attic floors decreases from 60 to 40%. For multi-storied buildings the nature of the structural changes in a building envelope with an increase in the number of stories, on the whole, remains the same, but quantitative values are different. With an increase in the number of stories from 4 to 25 the share of walls increases roughly from 40 to 65%, that of windows, from 10 to 22%, while the total contribution of ceilings and attic floors decreases from 50 to 13% (see Fig. 3). Abrupt changes in geometric characteristics k_i^F and ω_i with the change-over from low-rise buildings to high-rise ones are due to the differences in a ratio between the area of a foundation and the height of buildings related to building standards. It follows from the quantitative assessments presented here that, when the values of R_i are the same, low-rise buildings are obviously less energy-efficient than high-rise ones. Therefore, when predicting demands of the housing sector for thermal energy, it is necessary to take into account the structure of newly constructed buildings.

For the long-range macroeconomic conditions accepted here, there were obtained optimum values of the resistance of building envelopes to heat transfer for the existing housing stock in Russia when the buildings are insulated during major repairs (Table 5) and for newly constructed buildings (Table 6). These values turned out to be considerably more stringent than standards that are in force at present (see Table 1). Only under climatic conditions in Siberia (Novosi-

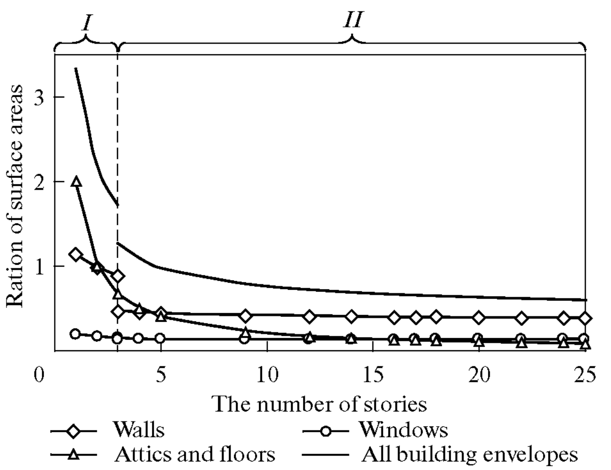

Fig. 2. A ratio between the surface area of envelopes and the total floor area of rooms for buildings with different number of stories. *I*—individual buildings (1–3 stories); *II*—multistoried apartment buildings (4—25 stories).

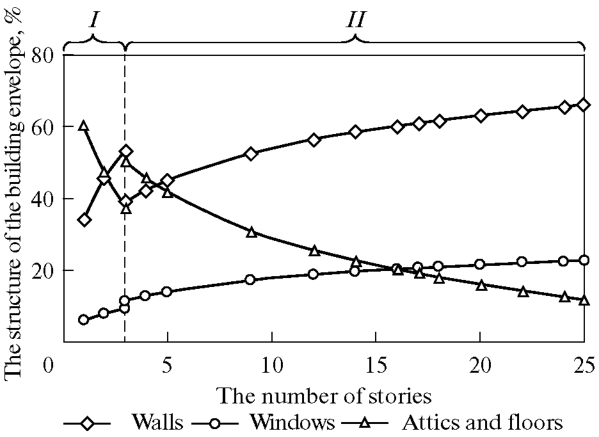

Fig. 3. Contribution of the envelopes of different types to the total surface area of the envelopes for buildings with different number of stories. Notations see Fig. 2.

birsk) the optimum values *R* for basement ceilings and attic floors do not exceed normative values, and the reason for this is that thermal energy tariffs in the Siberian region are low. To the highest degree the tightening of normative values of *R* apply to windows and glazed balcony doors. Under severe climatic conditions of Russia it is advisable to call for their maximum heat insulation. The obtained optimum values of *R* for windows are considerably higher than those of the best models currently available in the market (about 1.05–1.35). This implies that it is necessary to continue the improvement of transparent structures for the purpose of enhancing their thermal protection performance. For newly constructed buildings the optimum values of *R* approximate the corresponding values adopted in most northern countries, but in some respects they are considerably lower than the rigorous standards adopted in Denmark and Sweden, countries which are in the lead in the field of thermal protection of buildings (see Table 3).

The change-over to new standards for the resistance of building envelopes to heat transfer (see Table 6) would make it possible to reduce by a factor of 1.4 the specific heat losses in buildings with various number of stories (Fig. 4), in particular, for nine-storied buildings—from 43 to 32 W/m^2, while for two-storied buildings, from 70 to 52 W/m^2. It should be noted that the previous tightening of normative values of *R* provided reduction in specific heat losses in low-rise buildings by a factor of about 1.9, while in high-rise ones, by a factor of 1.5 (lines *1* and *2*, see Fig. 4).

On tightening normative values of *R*, heat losses due to infiltration become dominant in the structure of heat losses in buildings (Fig. 5). On achieving the optimum values of *R* the share of these losses exceeds 40%

Table 5. Optimum values of the resistance of envelopes to heat transfer for existing residential buildings, (m^2 K)/W

City	Type of a building envelope			
	walls	windows and glazed balcony doors	ceilings and floors	
			basement ceilings	attic floors
Moscow	3.95	1.20–1.55	4.40	4.40
St. Petersburg	3.50	1.05–1.35	3.95	3.95
Rostov-on-Don	3.60	1.10–1.40	4.00	4.05
Pyatigorsk	3.30	1.00–1.30	3.75	3.75
Nizhni Novgorod	3.85	0.54–1.50	4.30	4.30
Yekaterinburg	4.10	1.25–1.60	4.59	4.60
Novosibirsk	3.75	0.63–1.45	4.87	4.87
Khabarovsk	5.05	1.50–1.90	5.50	5.50

Note: Lesser values correspond to multi-storied buildings, greater values, to low-rise ones.

Table 6. Optimum values of the resistance of envelopes to heat transfer for newly constructed residential buildings, (m^2 K)/W

City	Type of a building envelope			
	walls	windows and glazed balcony doors	ceilings and floors	
			basement ceilings	attic floors
Moscow	4.60	1.25–1.55	4.50	4.50
St. Petersburg	4.15	1.10–1.40	4.06	4.06
Rostov-on-Don	4.25	1.10–1.45	4.10	4.10
Pyatigorsk	3.95	1.05–1.35	3.85	3.85
Nizhni Novgorod	4.55	1.20–1.55	4.40	4.40
Yekaterinburg	4.80	1.25–1.60	4.70	4.70
Novosibirsk	4.45	1.20–1.50	4.87	4.87
Khabarovsk	5.75	1.50–1.95	5.55	5.55

Note: Lesser values correspond to multi-storied buildings, greater values, to low-rise ones.

in low-rise buildings and 60% in high-rise ones. Hence, the further increase in the thermal efficiency of buildings should be associated, first and foremost, with a decrease in heat losses due to infiltration by means of implementing new technologies of indoor climate control [9–13].

On heat insulation of buildings the share of heat released into the space as a result of human activities in the heat balance of a building increases essentially (Fig. 6). This involves a considerable reduction in the need for heat supply to the building from outside. In newly constructed buildings with the optimum value of R the share of heat released into the space as a result of human activities in the heat balance of a building exceeds 40%. For buildings that at present are under construction according to the standards in force, the value of this coefficient is 30%, while for buildings that have been constructed before the year 2000, it is 19%. For example, for a nine-storied building with an optimum value of R at heat losses of 32 W/m^2 (at t_{out} under climatic conditions of Moscow) and heat released into the space as a result of human activities in the amount of 13 W/m^2, it is necessary to supply from the outside only 19 W/m^2. In low-rise buildings the contribution of heat released into space as a result of human activities to the heat balance of a building is less. However, in two-storied buildings at the optimum value of R this contribution may run to 25% against 8% for similar buildings, which have been constructed before the year 2000, and 18% for buildings that are under construction according to the standards in force.

As a result of the analysis of the sensitivity of the R value to the changes in external factors that has been carried out in order to find an optimum value of R, it became evident that the relationship γ_t, between predicted rates of thermal energy tariffs and the cost of heat insulation materials, i.e.,

$$\gamma_t = \prod_{\tau=1}^{t} I_\tau^q \Big/ \prod_{\tau=1}^{t} I_\tau^K$$

is very important.

During the forecast period, for the adopted values of macroeconomic indices (see Table 4), the parameter γ_t increases steadily (Fig. 7). This means that conditions for energy saving become more and more favorable. An increase in the parameter γ_t relative to the adopted forecast values of γ_t^0, i. e., $\gamma_t = k^\gamma \gamma_t^0$, brings about an increase in an optimum value of the resistance of building envelopes to heat transfer (Fig. 8). On increasing the coefficient of displacement k^γ to 2 the

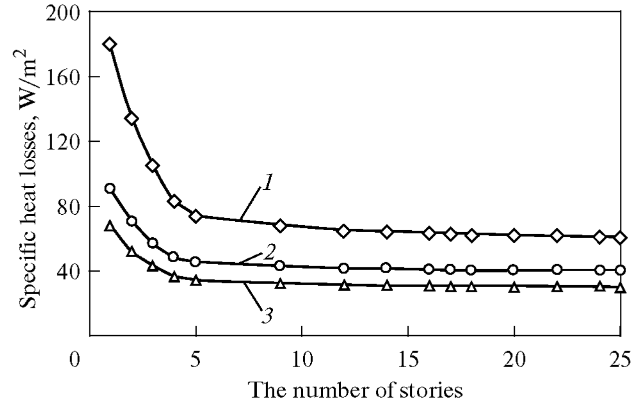

Fig. 4. Specific heat losses in buildings with different number of stories at t_{out} (under conditions of Moscow). *1*—building constructed before the year 2000; *2*—buildings that are constructed according to the existing standards for R; *3*—new buildings at optimum values of R.

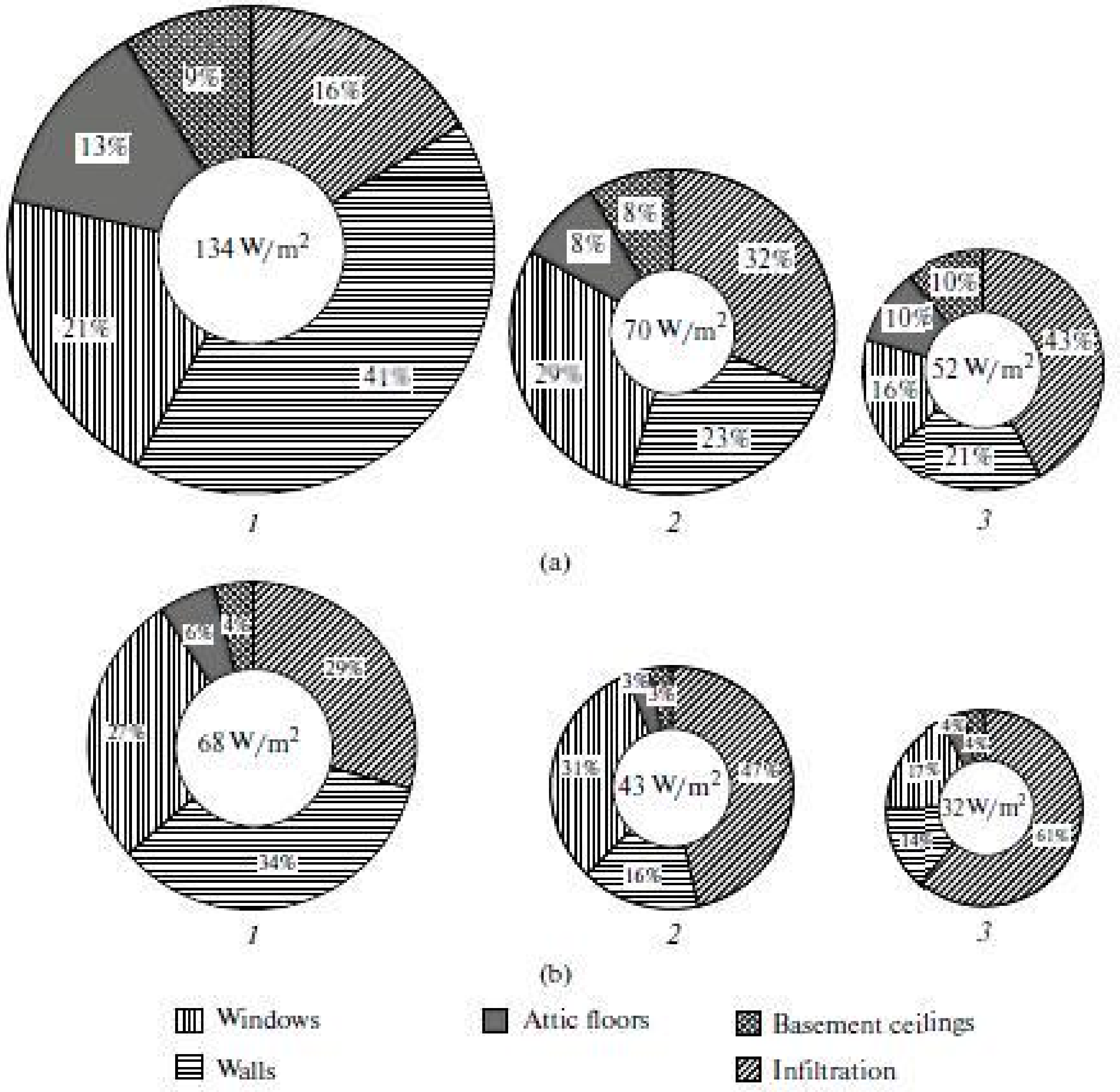

Fig. 5. The structure of heat losses in individual (two-storied) buildings (a) and in apartment (nine-storied) buildings (b) (at t_{out} under conditions of Moscow). Notations see Fig. 4.

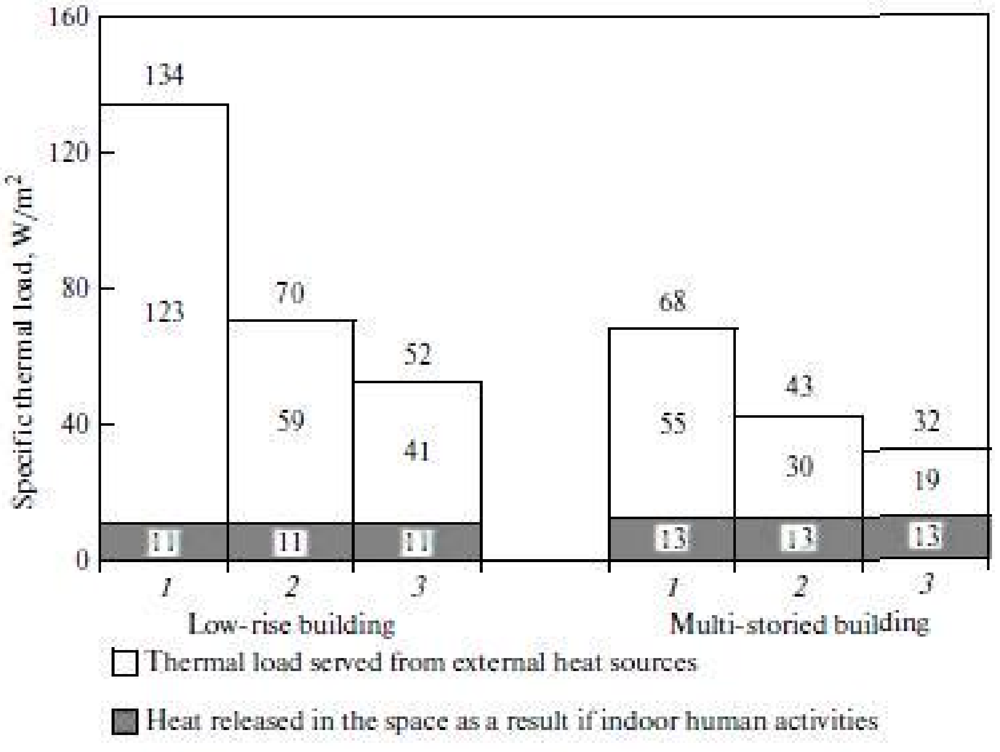

Fig. 6. Specific thermal load of buildings served from external heat sources (at t_{out} under conditions of Moscow). Notations see Fig. 4.

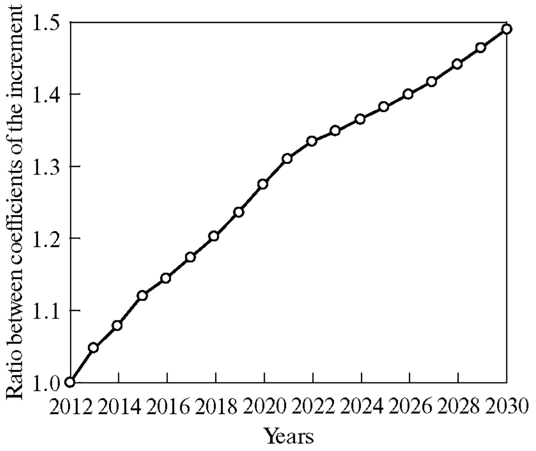

Fig. 7. Values of the parameter γ_t during the forecast period.

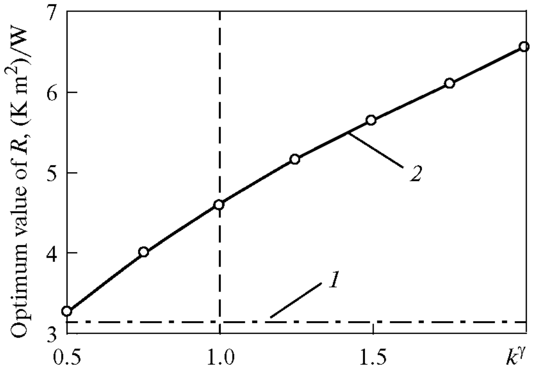

Fig. 8. The effect of the coefficient of displacement k^γ on the optimum values of the resistance of walls to heat transfer. *1*—Normatives now in force [2]; *2*—optimum values of *R*.

value of the optimum value of *R* for walls (under climatic conditions of Moscow) increases from 4.6 to 6.5.

Another important parameter that determines the optimum value of *R* is the real bank credit interest rate p_τ^r, which is due to high capital intensity of energy saving measures (Fig. 9). Reduction in the interest rate results in an increase in the optimum value of *R*. For example, on reducing p_τ^r from the present 6% to 4%, the optimum value of *R* for walls under climatic conditions of Moscow increases from 4.5 to 5.2% and reaches the normative requirements existing in Denmark, where the value of p_τ^r is considerably lower than in Russia.

The obtained optimum values of *R* made it possible to estimate the energy saving potential for both the existing housing stock and newly constructed residential buildings, when the resistance of building envelopes to heat transfer is brought to optimum values (Tables 7, 8). An increase in thermal efficiency of existing multi-storied buildings at the total scope of renovation equal to 1876 million m^2 might provide annual savings of thermal energy delivered by means of a centralized heat supply system in the amount of about 439 million GJ. This comes to almost 29% of its consumption for space heating, or 21.3% of the total heat consumption in the housing sector at present. For these purposes capital investments in the amount of about 1429 billion rubles are needed (with due regard for discounting and price rise). The payback period in most federal subjects is from 15 to 18 years. It is shorter in the Far East (from 12 to 13 years) and longer in Siberia (from 21 to 24 years), in the first case, because of high, while in the second case, on the contrary, because of low thermal energy tariffs. Similar effects are observed as the thermal effectiveness of low-rise buildings increases, although in this case the total scopes of renovation are 2.5 times less—751 million m^2 (see Table 7).

Tightening of normative requirements on the value of *R* for new buildings is more efficient economically. This will make it possible to save by the year 2030 about 108 million GJ of thermal energy annually, with the planned construction of new high-rise residential buildings with the total floor area of 1356 million m^2 (see Table 8). The necessary capital investments in the amount of 201 billion rubles will recoup themselves in the regions of the Russian Federation in 8–14 years. By the year 2030, in the course of construction of low-rise residential building with the total floor area of 511 million m^2, about 75 million GJ of thermal energy will be saved annually, and the payback period will be from 8 to 11 years.

Specific capital investments necessary to bring *R* to its optimal values when they are related to 1 GJ of saved thermal energy per year, are for the existing housing stock about 3.2 thousand rubles/GJ per year,

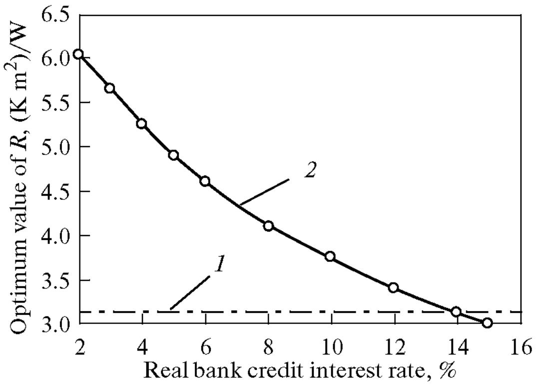

Fig. 9. The effect of a real bank credit interest rate on the optimum value of *R* for walls (under conditions of Moscow). Notations see Fig. 8.

Table 7. Energy saving potential in the existing housing stock in the case when R is brought to optimum values

Federal district	Renovated housing stock, million m^2	Capital expenditures, billion rubles	Annual thermal energy saving, million GJ/yr	The total saving of expenses over the period, billionn rubles	The total economic effect, billion rubles	Payback period, years
Multi-stories (apartment) buildings						
Russia	**1876**	**1429**	**439**	**2184**	**755**	**12–24**
Central	556	500	151	813	313	15–16
Northwestern	219	183	58	255	72	18–20
Southern	137	120	29	193	73	15–17
North-Caucasus	76	63	17	94	31	16–18
Volga	385	206	65	305	99	16–18
Urals	173	153	50	208	55	18–20
Siberian	242	117	41	143	26	21–24
Far Eastern	87	88	27	173	85	12–13
Individual (low-rise) buildings						
Russia	**751**	**1443**	**465**	**2345**	**902**	**11–22**
Central	188	405	132	708	303	14–15
Northwestern	60	121	42	183	62	16–18
Southern	89	187	50	326	139	14–15
North-Caucasus	64	127	38	206	79	15–16
Volga	174	293	94	439	146	16–18
Urals	46	98	35	148	50	16–18
Siberian	100	139	50	176	37	20–22
Far Eastern	30	73	25	160	87	11–13

while for newly constructed buildings they are 1.75 times less, about 1.8 thousand rubles/GJ per year.

CONCLUSIONS

(1) The predicted leading growth in prices for energy carriers as related to other macroeconomic indices offers favorable conditions for energy saving in the housing sector.

(2) It is advisable to considerably tighten the requirements on the normative values of the resistance of building envelopes to heat transfer for residential buildings, above all, the resistance of windows and glazed balcony doors. It is necessary to develop new heat insulating materials and structures, first of all, transparent ones.

(3) When tightening the requirements on the values of the resistance of building envelopes to heat transfer, heat losses due to infiltration, which exceed 40% in low-rise buildings and 60% in high-rise ones, become dominant in the structure of heat losses in buildings. A further increase in the thermal effectiveness of buildings should be, first and foremost, correlated with a reduction in heat losses due to infiltration and the development of appropriate technologies.

Table 8. Energy saving potential for newly constructed buildings at the optimum values of R

Federal district	Commissioning of new residential buildings, million m^2	Capital expenditures, billion rubles	Annual thermal energy saving, million GJ/yr	The total saving of expenditures over the period, billion rubles	The total economic effect, billion rubles	Payback period, years
Multi-storied (apartment) buildings						
Russia	**1356**	**201**	**108**	**465**	**264**	**8–14**
Central	275	47	23	106	59	10–12
Northwestern	103	13	8	29	16	10–12
Southern	263	42	21	111	68	8–11
North-Caucasus	122	17	10	42	25	9–11
Volga	214	32	18	70	38	10–12
Urals	131	19	12	40	22	10–12
Siberian	194	19	13	38	19	11–14
Far Eastern	56	12	6	29	17	9–11
Individual (low-rise) buildings						
Russia	**511**	**133**	**75**	**330**	**197**	**8–11**
Central	102	31	16	73	43	9–11
Northwestern	27	5	4	13	8	9–11
Southern	117	36	17	94	58	8–10
North-Caucasus	58	14	8	37	22	9–11
Volga	116	29	17	69	40	9–11
Urals	35	8	6	19	11	9–11
Siberian	47	5	5	14	9	8–10
Far Eastern	511	133	75	330	197	8–11

(4) An increase in the thermal effectiveness of existing multi-storied buildings might provide annual saving of total heat consumption in the housing stock in the amount of about 21.3%. The payback period required for this, in most subjects of the Russian Federation, varies from 15 to 18 years. An improvement in thermal protection properties of buildings under construction will provide a more considerable economic effect. In this case the payback period in the regions of Russia will be from 8 to 14 years.

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