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INSULATION OF HIGH-STOREY RESIDENTIAL BUILDINGS IN THE TERRITORY OF URBAN COMMUNITIES AND DETERMINATION OF ITS ENERGY-ENVIRONMENTAL EFFICIENCY

The object of research is the «boiler plant – heat consumers – environment» system, which is caused, in particular, by high fuel consumption by city boilers serving high-rise residential buildings, including a significant number of buildings of an outdated housing stock, which are characterized by a low level of energy saving.

One of the most problematic areas is the increase in emissions of pollutants and greenhouse gases into the atmosphere by boiler units and other power plants, especially during the heating season.

In the course of the research, an assessment and analysis of the level of pollution of the city's atmosphere by emissions from boiler plants, taking into account background pollution, and an analysis of the normative calculation method for determining emissions of pollutants into the atmosphere from power plants were used. The theoretical justification of the method of operational determination of current emissions of urban boiler houses and indicators of their energy-ecological efficiency based on current daily fuel consumption recorded during the entire heating season is also given, with a simultaneous assessment of the energy efficiency of fuel use and the degree of ecological hazard of emissions. The essence of the method is to use the indicator (energy-ecological index) introduced by the authors – K. This indicator simultaneously characterizes the multiplicity of exceeding both the current fuel consumption and the corresponding current emissions of pollutants by the boiler room, relative to their reference (reference) values determined once at the beginning of the heating season at an ambient air temperature of about 8 °C. The proposed temperature method for determining the K index before and after the implementation of both resource-saving technologies and technologies for protecting the atmosphere from emissions in the «boiler plant – heat consumers – environment» system allows to evaluate their effectiveness by the level of reduction in the value of the index, compared to its previous value, that is, to implementation obtained under similar conditions.

It has been proven that in order to obtain a tangible energy-ecological effect at the level of a large city from its technology of warming the walls of buildings, its mass centralized implementation is necessary, both for individual high-rise buildings and on the scale of existing residential neighborhoods. For the reconstruction of existing facades, it is proposed to use current industrial technologies for warming the walls of buildings, which are used in new buildings, which are based on the use of mineral wool, in particular ISOVER-plaster. Insulation of walls with ISOVER-plaster will have the following advantages compared to foam plastic: thermal conductivity coefficient – 0.034 W/m·K, against 0.048 W/m·K for foam plastic. When using plates with a thickness of 100 mm ISOVER-plaster is expected to reduce heat loss to approximately 2.8 %, against 2.17 % obtained for foam plastic, which will provide a correspondingly greater energy and ecological effect.

Keywords: *ecological danger of heat supply systems, methods of determining emissions of pollutants into the atmosphere, insulation of buildings.*

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1. Introduction

Environmental safety in the territories of urban communities is due, on the one hand, to high fuel consumption, in particular boiler plants that serve high-rise residential buildings with a low level of energy saving, and on the other hand, to relatively high emissions of pollutants and greenhouse gases into the atmosphere [1–7]. Municipal enterprises of heat networks perform an important function, ensuring the supply of heat and hot water to administrative residential buildings. However, from the point of view of environmental safety, especially of large industrialized cities, such enterprises are sources of environmental pollution, in particular due to emissions of pollutants into the atmosphere and rather intensive consumption of fuel, including natural gas – a strategic fuel resource nowadays,

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the burning of which and causes emissions. Thus, in cities with a large population, each district has from 4 to 8 centralized boiler houses and a large number of boiler houses of smaller capacity, operating mainly on natural gas. Despite the fact that gas is a relatively harmless fuel, it still emits a significant amount of pollutants into the atmosphere, including nitrogen oxides (NO_x) and carbon monoxide (CO), as well as heavy metals, in particular mercury (Hg). This worsens the environmental situation in the areas, especially during periods of peak loads, not to mention boiler plants that consume coal, fuel oil, pellets, while emitting sulfur oxides and a number of other environmentally hazardous substances. It is in the coldest periods of the heating season that there are significant deviations of the operating modes of boiler plants from the nominal ones in the direction of increased fuel consumption, including due to insufficient quality of its combustion in excessively loaded boiler units. This, accordingly, leads to increased emissions into the atmosphere of pollutants entering the air together with the flue gases of boiler houses.

The solution of these issues is connected with carrying out:

– thermal modernization of buildings through insulation of external walls, attics, roofs, etc., as well as replacement with more energy-efficient windows and doors;
– modernization of engineering systems;
– increasing the useful use of energy due to the use of recuperators, thermostats, heat pumps and other latest energy-saving technologies. The implementation of thermal modernization measures will contribute to increasing the service life of buildings in the city's residential sector.

Thus, *the object of research* is the «boiler plant – heat consumers – environment» system, which is caused, in particular, by high fuel consumption by city boilers serving multi-story residential buildings, including a significant number of buildings of the outdated housing stock, which are distinguished by a low level of energy saving. And *the aim of research* is to justify the calculation method of operational determination of current emissions (emissions) of pollutants entering the atmosphere together with flue gases of seasonal urban boiler houses, according to the intensity of daily fuel consumption by boiler units with a simultaneous assessment of the energy efficiency of fuel use and the degree of environmental hazard of emissions.

2. Materials and Methods

In the course of the study, an assessment and analysis of the level of pollution of the city's atmosphere by emissions from boiler plants, taking into account background pollution, and an analysis of the normative calculation method for determining emissions of pollutants into the atmosphere from power plants were used.

As part of the evaluation of heat loss by buildings of an outdated housing stock, the evaluation of heat loss by a typical 5-story residential building was performed [8]. It was assumed that the walls of the building are made of silicate brick, the thermal conductivity of which is equal to $\lambda = 0.7$ W/m·degree K. The thickness of the walls is $d = 0.4$ m. Approximate dimensions of a typical five-story building with 3 entrances: length $A = 60$ m, width $B = 15$ m, height $H = 15$ m. The total area of walls S, through which heat flows to the outside, is about 3150 m^2. As a result, under the conditions, if the temperature $T_1 = +20$ °C is maintained inside, and frosty air with temperature $T_2 = -10$ °C is outside the windows, the power of heat losses due to the thermal conductivity of the general surface, as the walls will be [9]:

$$W_1 = S\lambda(T_1 - T_2)/d = 3150 \cdot 0.7 \cdot 30/0.4 \approx 165 \text{ kW}. \quad (1)$$

If to take into account the presence of windows, heat loss will increase to approximately 202 kW. At the same time, with normal ventilation, the building loses about 135 kW, and taking into account drafts, another 140 kW. Therefore, the total heat loss capacity of a 5-story building with a total surface area of 3150 m^2 reaches 480 kW [8]. In terms of an area of 1000 m^2, which is convenient to use in large-scale calculations of heat loss by houses, it will be about 160 kW/1000 m^2.

For comparison, let's present the generalized results obtained for a new residential single-section, typical for large cities, 25-story building, which was designed, in particular, taking into account seasonal heat supply in the climatic conditions of the city of Kyiv (Ukraine) [9]. At the same time, heat transfer through certain areas of the building for each degree of atmospheric air temperature, W/K, is indicative (Table 1).

According to the Table 1, given in columns 3 and 4 in the last line, let's estimate the average heat loss of this house at a temperature of $t_a = -10$ °C (263 K) as: $W = 4882 \cdot 263/9230 = 139$ W/m^2 or 139 kW/1000 m^2, that is, as expected, for new buildings there is a value that is 13 % lower than the similarly majestic value of 160 kW/1000 m^2 obtained above for a building of an outdated housing stock.

Table 1

Comparative characteristics of heat transfer by transmission through individual structures of the house according to a priori data

No.	Building area	Area of the heat transfer zone, m^2	Heat transmission, W/K	Specific heat transmission, W/(m^2·K)	Share of the total transmission of heat by the house, %
1	Outside walls	7330	3321	0.453	68
2	Combined coating	60	20	0.333	0.41
3	Covering the cold attic	415	135	0.325	2.76
4	Overlap over the technical underground	475	233	0.490	4.77
5	Translucent structures (windows)	442.5	590	1.333	12.1
6	Translucent structures behind glazed balconies	497.5	564	1.134	11.55
7	Entrance door	10	20	2	0.41
	Σ	9230	4882	6.068	100

In order to compare the calculated values with actual values, let's use the results of the heat loss study of a 5-story building of an outdated fund by radiation on the basis of a temperature survey using a radiation pyrometer [10], which indirectly characterize all heat losses of the building. The experiments were carried out in December-January on cloudy days with no wind, which made it possible to exclude the influence of direct solar radiation on the temperature of the facade wall surfaces. Pyrometer measurements were performed as shown in Fig. 1.

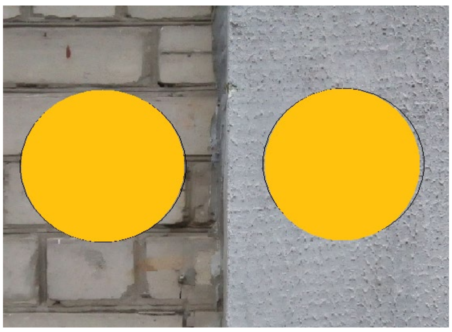

Fig. 1. Areas of scanning the surface of the brick facade wall with a pyrometer: *a* – without the presence of fragmentary insulation; *b* – in the presence of fragmentary insulation [10]

The diameter of the temperature scanning zone was approximately 20–30 cm. The heat loss per unit area of the house wall was estimated from the data of the radiant temperature of the wall surface as:

$$B=\delta\sigma T^4, \quad (2)$$

where $\sigma=5.67032\times10^{-8}$ W/m^2·K^4 – the Stefan-Boltzmann constant; $\delta=0.95$ – correction for a gray body, which was considered the wall of a house made of silicate brick; T is the surface temperature of a heated body on the Kelvin scale (related to the Celsius scale, as $T=t$ °C+273).

The comparative assessment was performed at the average surface temperature of the brick wall over the period of the research, which was 3.57 °C. As a result, the estimated amount of heat loss through the brick wall was:

$$B_{1000}=1000\delta\sigma T^4=1000\cdot5.67032\cdot10^{-8}\times$$
$$\times0.95\cdot(3.57+273.15)^4=315.86\ \text{kW/1000 m}^2.$$

This estimated power turned out to be almost twice as much as the above heat losses of 160 kW/1000 m^2 for a similar 5-story building. The discrepancy is due to the approximate choice of the calculation parameters of the house and certain theoretical assumptions. However, the obtained estimated results of heat loss by radiation are quite acceptable for further comparative analysis of the energy-ecological efficiency of building insolation measures before and after their application.

In order to determine the energy-ecological efficiency of the introduced house warming technologies, an estimate of the reduction of heat loss by the house when applying the wall warming technology with the use of foam panels was obtained. which was also obtained based on the results of field surveys with a radiation pyrometer of the temperatures of insulated wall fragments, but compared to the heat loss of the brick surface of the wall, determined above at a temperature of 3.57 °C. This averaged temperature corresponds to the calculated temperatures of the surfaces of foam insulation with a thickness of 5 and 10 cm, which according to the corresponding regression equations shown in Fig. 2 [10], were: 2.287 °C and 2.055 °C, and the corresponding heat losses by radiation from their surfaces according to formula (2) were determined as: 310.04 and 309 kW/1000 m^2.

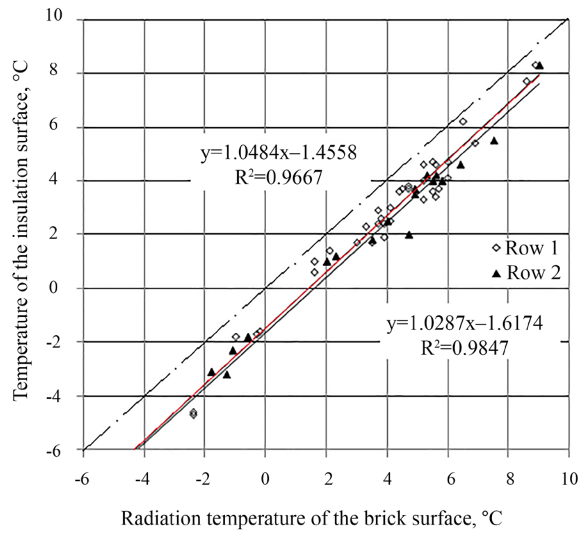

Fig. 2. Dependence of the temperatures of the surfaces of the insulation on the temperature of the surface of the brick, determined by the pyrometer: Row 1 (linear trend and the corresponding regression equation from above (red line)) – for insulation with a thickness of 5 cm; Row 2 (corresponding attributes from below) – for insulation with a thickness of 10 cm; dashed line with the tangent of the angle of inclination 1 – the graph of the surface temperature equation of the brick [8]

It should be noted that the obtained average heat loss discounts of 2 % will be typical for each selected area of the insulated surface, that is, for a separate foam-insulated individual house, or on the scale of a block or microdistrict. Moreover, such a relative decrease will also be characteristic of the values of fuel consumption, emissions of pollutants and the corresponding energy-ecological indexes K_i, proposed in work [10] to determine the resource-saving and ecological effects in the system «boiler plant – heat consumers – environment» from the introduction of resource-saving technologies in it.

Let's recall that the current values of the index are defined as:

$$K_i=B_i/B_{8C}=E_j/E_{j8C}, \quad (3)$$

where B_i, B_{8C} – respectively, the daily fuel consumption of the boiler room and the reference value of its daily consumption, determined at the beginning of the heating season and adjusted to a temperature of 8 °C; E_j, E_{j8C} – respectively, the current emission of the j-th pollutant in the composition of flue gases by the boiler house and the reference value of the emission, calculated by the value – B_{8C}.

For example, with a daily fuel consumption of a boiler capacity of 10 MW (approximately this capacity has a typical TVG-8m gas water heating boiler unit with a nominal capacity of 9.6 MW), which is B_i=19.64 t/day

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at the average temperature of the atmosphere during the heating season t=0 °C (corresponds approximately to the nominal capacity of the boiler unit), and the amount of fuel consumption at the beginning of the season according to a priori data was estimated as $B_{8C}\approx 12.5$ t/day, then let's obtain the value K_{i0}=1.5712. After the full-scale implementation of insulation of walls (facades) with polystyrene plates in the buildings of the city's outdated housing stock, the value of the energy-ecological index will decrease by an average of 2 % to the level of K_i=1.5397, i. e. it will be below the predetermined value by 0.0315. This characterizes the obtained energy-ecological effect from the proposed wall insulation technology.

According to (3), the emissions of each pollutant and their concentrations in the flue gases of the boiler room, as well as fuel consumption by the boiler unit, will be reduced accordingly. Thus, the concentration of nitrogen oxides NO_x in the flue gases of the boiler house will decrease from the nominal value of 250 mg/m^3 to 245 mg/m^3, and carbon monoxide CO – from 130 mg/m^3 to 127.4 mg/m^3, that is, it will decrease by 5 mg/m^3, respectively and 2.6 mg/m^3. The consumption of B_i fuel by boiler units will decrease to the level of 19.246 t/day, that is, the daily consumption of fuel will decrease by 394 kg/day.

For further assessment of the level of reduction of environmentally hazardous emissions into the atmosphere by boiler houses of the city community, let's use the a priori data of the company of heat networks of the city of Dnipro (Ukraine). In general, the emission of gaseous environmentally hazardous substances is of the order of 3300–3500 t/year, in particular nitrogen oxides approximately 118 g/s, carbon monoxide – 37 g/s. All sources of emissions are located on 7 conditional sites of the city territory. Therefore, they are actually a source of pollution of the city atmosphere scattered throughout the city. This, on the one hand, affects the level of ecological safety of the city's territories due to the flue gases formed as a result of burning fuel, and on the other hand, determines the level of consumption of valuable fuel resources, since emissions are proportional to fuel consumption by boiler rooms. The calculated values of the formed concentrations of pollutants are given in the Table 2.

From the Table 2, it follows that the contribution to the emissions of pollutants into the atmosphere by the boilers of the city's heat network enterprise, defined as the difference between the data in the 8th and 4th columns of the table, is:

– for nitrogen dioxide: 5.07–4.3=0.77 MPC;
– for nitrogen oxide: 2.8–2.66=0.14 MPC;
– for carbon monoxide: 1.57–1.560=0.01 MPC.

That is, emissions from boiler houses do not exceed the MPC, but taking into account the background concentrations caused by emissions of these gases from other sources, which in the conditions of the city exceed the MPC (column 4), let's obtain an additional increase in the MPC multiplication of the indicated pollutants in the atmosphere (column 8). At the same time, the contribution of boiler plants to the total (together with the background) concentration of such an environmentally hazardous substance as nitrogen dioxide is about 18 %, and in the sum with other oxides, it is up to approximately 20 %. This makes it possible to classify city boiler houses as one of the significant polluters of the city's atmosphere, which ultimately increase the overall pollution of the city's atmosphere, mainly in the heating season. Therefore, after large-scale insulation of the facades of buildings, the relative contribution of the boiler oxides listed above will decrease from 20 % to 2 %, that is, to 18 %. In absolute terms, emissions of gaseous environmentally hazardous substances will decrease by approximately 68 t/year.

Now let's estimate the emissions of carbon dioxide (CO_2) – the main vapor-blood gas that affects the climate – by the company's heating networks of the city. Let's note that according to data [11], emissions of pollutants into the atmosphere, compared to 2014, decreased by approximately two times, and amounted to 537.6 thousand tons in the region. At the same time, 22.300 thousand tons of carbon dioxide entered the atmosphere, that is, 41.5 times more than the mass of pollutants. Focusing on this multiplicity and amount of emissions of polluting gases in the city of Dnipro in 2021 – 28.62 thousand tons, let's obtain the estimated amount of urban emissions of carbon dioxide: 28.62·41.5=1187.7 thousand tons. Similarly, at average emissions of 3,400 t/year from boiler houses of the city's heat networks, let's obtain the estimated amount of carbon dioxide emissions by public boiler houses as: 3,400·41.5=141,100 t/year, that is, 141,100 t per year, which is approximately 12 % from the mass of urban emissions of this greenhouse gas. After large-scale insulation of the facades of city high-rise buildings, this share will decrease from 12 % to 10 %, or from 141.1 thousand tons to 118.8 thousand tons.

Table 2

Concentrations of pollutants emitted into the atmosphere by boiler rooms of the city's heat network enterprise

Pollutant name	Pollutant concentrations						
	MPC, mg/m^3	Background		Calculated and taking into account the background for the field source*			
		C_{back}, mg/m^3	MPC share	C^*, mg/m^3	$C^*_{back}=C_{back}$ (1–0.4·C^*/C_{back}), mg/m^3	$C^*+C^*_{back}$, mg/m^3	MPC share
Nitrogen dioxide	0.04	0.172	4.3	0.052	0.151	0.203	5.07
Nitrogen oxide	0.06	0.160	2.66	0.014	0.155	0.168	2.8
Carbon monoxide	3.00	4.683	1.56	0.025	4.673	4.698	1.57

Notes: C^* (column 5) – the sum of the maximum surface concentrations for plane sources for this pollutant, determined during the analysis of the scattering calculation using the «EOL-2000» program; C^*_{back} – the value of the background concentration of the substance, from which the contribution of the considered source of the enterprise for this substance was subtracted. It is defined as: $C^*_{back}=C_{back}(1-0.4\cdot C^*/C_{back})$, mg/m^3; C^*+C_{back} (column 6) – the sum of the maximum surface concentrations of this substance and the background concentration at the border of the sanitary protection zone of boiler houses

3. Results and Discussion

As a result of the analysis of previously conducted studies [8, 10], let's conclude that old buildings need a certain reconstruction in terms of heat preservation. Moreover, as follows from the analysis of the Table 1, the main rational solution is the reduction of thermal energy consumption by increasing the insulating properties of the external walls, i. e. the facade system of the house, which reach 68 % of total losses. First of all, this applies to new buildings, but it is also relevant for buildings that have been in operation for a considerable time and are subject to major repairs based on modern approaches to the reconstruction of their facade systems, taking into account the monitoring of the energy efficiency of such buildings. Including, according to the losses of thermal energy through their front walls, the level of fuel consumption for heating and the corresponding emissions of environmentally hazardous gases by boiler rooms.

Therefore, with the use of the specified insulation, heat loss through the facade walls will decrease by 5.82 and 6.86 kW/1000 m^2, respectively, that is, on average, by 6.34 kW/1000 m^2, and in relative terms: by 1.84 % and 2.17 %, i. e. by 2 % on average, with a relative error of +/–8 %.

Finally, let's estimate the specific amount of carbon dioxide emissions by a boiler capacity of 10 MW at the nominal consumption of natural gas, which is about B_i=19.64 t/day. Taking into account that when burning 1 kg of natural (pipeline) gas, 2.64 kg of carbon dioxide and 2.09 kg of water vapor are formed, the daily emission of carbon dioxide by the indicated boiler house will be: 19640·2.64=51849.6 kg (51.85 t), and for water vapor: 19640·2.09=41047.6 kg (41.05 t), which, without the presence of condensers in boiler rooms, causes a much greater greenhouse effect than carbon dioxide. After the insulation of the facades, the consumption of natural gas will decrease to 19,246 t/day, and the daily emissions of greenhouse gases to 50.81 and 40.22 tons, respectively, and the specific daily emissions during the operation of boilers in the nominal mode will be 5,081 and 4,022 t/MW, respectively, that is, so many greenhouse gases are emitted into the atmosphere for each MW of boiler power.

The full-scale military aggression of the russian federation against Ukraine, destroying in 2022 all the fundamental principles of the international order system formed after the World War II, caused not only huge destruction of the Ukrainian industrial complex, settlements, transport, residential and energy infrastructure, but also caused significant damage to the environment.

In the process of post-war development of housing and energy infrastructure in Ukraine, the priority direction for our state is to focus on the components of development, namely energy efficiency and energy saving, with a corresponding increase in the level of environmental safety of urban areas.

Environmental safety in the territories of urban communities is due, on the one hand, to high fuel consumption, in particular boiler plants that serve multi-story residential buildings with a low level of energy saving, and on the other hand, to high levels of emissions of environmentally hazardous pollutants and greenhouse gases into the atmosphere.

The peculiarity of urban boiler houses, in particular of the seasonal type, is that with the gradual seasonal cooling, the consumption of fuel necessary to maintain the temperature of the coolant at the heat consumers at a given level increases, and accordingly, together with the flue gases, the emissions of pollutants into the atmosphere increase. In addition, the operational control of emissions from boiler houses is gaining relevance, which is necessary, on the one hand, to determine the emissions tax, the level of environmental safety of urban areas caused by these emissions, including at extremely low temperatures of the atmospheric air. And on the other hand, to determine the effectiveness of the implementation of both resource-saving technologies and technologies for protecting the atmosphere from emissions from power plants, in particular boiler units of city boiler houses.

Therefore, the calculation method of operational determination of current emissions of city boilers based on daily fuel consumption, which is recorded during the entire heating season, with a simultaneous assessment of the energy efficiency of fuel use and the degree of environmental hazard of emissions, is substantiated.

The essence of the method consists in the use of the introduced indicator (index) K, which simultaneously characterizes the multiple of the boiler room exceeding both the current fuel consumption and the corresponding current emissions of pollutants relative to their reference (reference) values determined once at the beginning of the heating season at an ambient air temperature of about 8 °C.

Large-scale insulation of the facade walls of the buildings of the old housing stock of the city community based on the use of current industrial technologies used in new buildings is also proposed. These technologies are based on the use of mineral wool, in particular ISOVER plaster, to obtain a tangible energy-ecological effect at the level of a large city.

Therefore, *the research results can be applied* among the industrial productions of Ukraine, where one of the biggest sources of environmental pollution is the energy industry, which is a source of emissions of pollutants into the atmosphere scattered over the territory of large industrial cities. Since energy production in the process of fuel consumption in power plants is accompanied by gaseous (oxides of carbon, nitrogen, sulfur) and dust emissions (soot, ash) into the atmosphere, depending on the fuel consumed. And also due to the fact that the issues of environmental safety in the territories of large cities are becoming relevant, as they are caused, in particular, by high fuel consumption by city boilers that serve multi-story residential buildings, including a significant number of buildings of an outdated housing stock. Old buildings have a low level of energy saving and, accordingly, require more energy for heating, which means more fuel, which leads to increased emissions of pollutants and greenhouse gases into the atmosphere by boilers and other power plants, especially during the heating season.

A limitation of the study is that insulation of the walls of buildings with mineral wool can be determined by different regulations, building codes or standards that regulate construction activities in a specific country or region. These standards can set minimum requirements for insulation thickness, quality of materials, installation methods and other parameters. Usually, the limitations of insulating the walls of buildings with mineral wool are determined with regard to thermal protection and energy efficiency of the building. This may include calculations of the thermal resistance of the walls, which must comply with standards and regulations. Restrictions on the use of specific types of insulation or

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installation methods may also be established in order to ensure the safety and quality of building structures.

4. Conclusions

In order to obtain a tangible energy-ecological effect at the level of a large city from the technology of warming the walls of buildings, its mass centralized implementation is necessary, both for individual high-rise buildings and on the scale of existing residential neighborhoods. For the reconstruction of existing facades, it is proposed to use current industrial technologies for warming the walls of buildings, which are used in new buildings, which are based on the use of mineral wool, in particular ISOVER-plaster. This cotton wool has advantages compared to foam plastic, in particular, the coefficient of thermal conductivity is 0.034 W/m·K, against 0.048 W/m·K for foam plastic, therefore, when using plates with a thickness of 100 mm, a reduction in heat loss is expected to approximately 2.8 %, against 2.17 % obtained for foam plastic, which will provide a correspondingly greater energy and ecological effect.

Conflict of interest

The author declares that she has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The manuscript has associated data in a data repository.

Use of artificial intelligence

The author confirms that she did not use artificial intelligence technologies when creating the current work.

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