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FEATURES OF ENERGY EFFICIENT UPGRADE OF HISTORIC BUILDINGS (ILLUSTRATED WITH THE EXAMPLE OF SAINT-PETERSBURG)

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In most European countries, including Russia, the requirements for building heat insulation are increasingly stringent. Historic buildings have become "energy inefficient" in terms of walling thermal upgrading aimed at reduced energy consumption. However, unlike the mass series of buildings, the historic ones are of cultural and architectural value. The energy efficient upgrade must not result in the lost of their historical authenticity. The article questions the applicability of existing standards for the thermal insulation of historic buildings, in particular, the "pros" and "cons" of walling thermal insulation. It discusses the need to preserve the exterior of the buildings that are monuments of history and culture as well as the historically-formed construction system. It puts forward the idea of improving the quality of indoor climate in residential buildings instead of energy savings at all costs.

Key words: Energy efficiency, Historic buildings, Reconstruction, Upgrading, Thermal insulation, Heat insulation

INTRODUCTION

Improved energy efficiency of historic buildings is one of the most urgent problems of construction science nowadays. Lower energy consumption and energy saving technologies make it possible to comply with the standards of sustainable development of the society and provide comfort to every household [03, 12]. Energy consumption of the municipal sector accounts for about 40 % of the total amount. So, reduced energy consumption is the main goal of energy-efficient renovation of old buildings. Besides, energy efficient upgrading of old buildings will improve the indoor climate, reduce the cost of electricity and heat, decrease carbon dioxide emissions, increase present value of the building and improve its condition and durability [08, 14, 33]. The conclusion is made on the basis of calculations and analysis that approach should be selective when it comes to historic buildings.

LITERATURE REVIEW

The concept of «Sustainable Buildings» includes several major interrelated notions: a comfortable indoor climate, maximum use of renewable energy, energy efficiency of the elements of the building as a whole [23]. Methods to achieve climate comfort in low energy buildings in the areas with the cold climate were described in many works, in particular in Y. A. Tabunshchikov, M. M. Brodach, P. Sormunen, H. Ehhort, J. Reiss, R. Hellwig, M. Morelli, H. Tommerup, L. D. Boguslavskiy, V. K. Savin, V. A. Yezerskiy, P. V. Monastyrev [5, 16, 17, 26, 27, 29, 30].

V. Fayst, I. Gabrieel, H. Ladener, D. Haas-Arndt, Burkhard S. Darup, Heinz P. Janssen, H. Rehkugler, T. Rombach, J. Reiß, H. Erhorn, M. Reiber made the great contribution in buildings reconstruction methods based on the energy-efficient home [04, 06, 08, 09, 11, 21, 22].

St. Petersburg has a great number of unique historic buildings. The research aims to raise energy efficiency of historic buildings which includes taking traditional measures to reduce energy consumption as well as reconciling the interests of cultural heritage protection with ongoing activities aimed at improving energy efficiency. Another aim of the research is to analyze the historically-formed construction system in terms of its energy and environmental qualities.

METHOD, CALCULATIONS, RESULTS

For St. Petersburg, the normalized value of heat consumption in residential buildings lies in the range of 55 kW\h to 118 kWh\m^2 per 1 m^2 (SNiP 23-02), compared to the target value of

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heat consumption in Germany which is EnEV 2009 and lies in the range of 30 to 70 kWh per year per 1m^2 of living space. The location of St.Petersburg more to the north should be taken into consideration [08]. One of the fundamental differences between the Russian standard for thermal protection and the national standards in most European countries is the consideration of the construction region in Russia. There is a notion of “degree-day heating season” as there are several climatic zones in Russia.

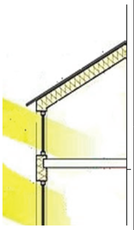
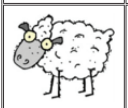
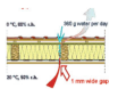
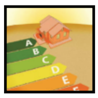
Russian Standard SNIP 23-02 “Design of building heat insulation” sets the requirements for:

1) Reduced total thermal resistance of building envelopes;
2) Inner surface temperature of the enclosing wall and prevention of condensation on the inner surface of the enclosing wall;
3) Specific consumption of heat energy for heating buildings.

The requirements for building heat insulation protection are considered fulfilled if the requirements of positions 1 and 2 or positions 2 and 3 are satisfied at the same time.

The set of measures to raise energy savings in buildings can be represented as a sum of energy conservation and energy generation based on renewable energy. Of the whole complex of measures energy efficiency provides the greatest effect at the lowest cost [18].

Table 1: Energy efficiency in buildings

Energy efficiency in buildings									
The concept of “passive house”				Optimization of energy consumption			Energy-efficient appliances and equipment		Intelligent Control Systems
Superinsulation		Utilization of domestic heat	Utilization of solar radiation						
Thermal insulation of walling	Pressurization of walling	Controlled ventilation		Energy accounting	Energy management	Energy consumption control	Indoor	Common use	
									

The special challenge is to develop the set of energy-saving measures for historic buildings, taking into account the uniqueness of the historically-formed construction system, as well as the need for the protection of cultural heritage objects.

The apartment house, a typical pre-industrial building of St. Petersburg, was chosen as an object of the study. This is a three-four-storey house built with the purpose of renting apartments. Each apartment usually occupied the whole floor.

Based on the analysis of archival drawings and technical documentation a typical structural diagram of an apartment building was identified. The author also carried out a visual inspection of buildings and took control measurements of the main geometrical parameters.

The results of the study showed that the historic buildings of St. Petersburg are characterized by changing with height wall thickness. Minimum thickness of the outer wall on the top floor was 2.5 bricks or 0.72 m, and 4 bricks (1.15 m) on lower floors. The peculiar "eternal" skeleton of the building is made of massive brick walls and basement vaults, with the floor and roof structure implying the possibility of periodic bulkhead. Even in the 19th century most of the buildings went through the reconstruction with the superstructure floor. The historic brick was solid and had dimensions of 280 mm x 140 mm x 70 mm, sand-lime mortar was used for laying bricks (Figure 1) [10].

a) b) c)

Figure 1: The exterior of the bricks manufactured:
a) at the end of the 18th century, b) at the beginning of the 19th century, c) at the end of the 19th century

The quality assessment of the heat insulation of the outer walls of historical buildings is conducted by thermal imaging method. Using the thermography, the hidden defects in the brickwork and the extreme humidity spots in the walls can be detected. [23, 24]. The original design conditions obtained for St. Petersburg on the basis of standards SNIP 23-01, SNIP 23-02 and SP 23-101 are shown in Table 2.

Table 2: Design conditions

	City - Saint Petersburg	Symbol	Units	Value
	Design ambient air temperature	t_{ext}	ºC	-26
	Design interior temperature	t_{int}	ºC	-1,8
	Duration of the heating season	z_{ht}	сут.	220
	Design interior temperature	t_{int}	ºC	20
	Operating conditions of walling	Type B (high humidity)		
	Relative humidity inside the building	φ	%	55
	Degree-day heating season	D_d	°C day	4796
	Coefficient taking into account the dependence of the enclosing structure position in relation to ambient air			n = 1
	Normalized temperature difference between the interior temperature and the temperature of enclosing structure inner surface	Δt_n	ºC	not more than 4
	Heat transfer coefficient of the enclosing structure inner surface	α_{int}	W/m² °C	8,7
	Heat transfer coefficient of the enclosing structure outer surface	α_{ext}	W/m² °C	23
	Dew point interior temperature for the cold season	t_d	ºC	10,7
	Normalized heat transfer resistance of enclosing structure	R_{req}	m² • C/W	3,0786
	Required thermal resistance of enclosing structure according to hygiene requirements $R= n (t_{int} - t_{ext})/ \alpha_{int} \Delta t_n$	R	m² • C/W	1,3218

Required values of reduced thermal resistance of other structures of residential buildings in relation to climatic conditions in St. Petersburg:

- roofs and ceilings above passages 4.60 (m^2 • C/W);
- attic ceilings, above unheated cellars and basements - 4.06 (m^2 • C/W);
- ground floor - 4.50 (m^2 • C/W);
- windows, balcony doors, shop and stained glass windows - 0.51 (m^2 • C/W);
- lamps with vertical glazing-0.37 (m^2 • C/W);

Modern standards stipulate the following requirements:

Requirement for design heat transfer resistance R_o, (m^2 • C/W) of enclosing structure, without heat transfer performance uniformity factor, is determined by the formula:

$R_o \geq R_{req}$,

taking into account heat transfer performance uniformity factor r:

$R_o \cdot r \geq Rreq$,

$Ro = 1/\alpha_{int} + (R1 + R2 + ...+ Rn)+1/\alpha_{ext}$,

The requirement for design temperature difference Δt_0 between the interior temperature and temperature of enclosing structure inner surface:

$\Delta t_0 \leq \Delta t_n$

$\Delta t_0 = n\,(t_{int} - t_{ext})/ R_o \cdot \alpha_{int}$

The requirement for minimum temperature in all areas of inner surface of exterior walls τint, °C in relation to dew point interior temperature t_d (without condensate formation).

$\tau int \geq t_d$

$\tau int = t_{int} - [n(t_{int} - t_{ext})]/(R_o \cdot \alpha_{int})$

The results of normalized parameters calculation for the historic buildings wall with 2.5 bricks thickness are shown in Table 3.

Table 2: The results of normalized parameters calculation for the wall thickness of 2.5 bricks

№ of layer	Material	δi, m	λi, W / (m • °C)	Ri, (m2* ºC)/W	Normal value
1	Interior plaster - lime-sand mortar	0,02	0,81	0,0247	
2	Brickwork 2.5 with ordinary clay brick density 1800 kg/m3	0,72	0,81	0,8888	
3	Stuccowork - sand-lime mortar	0,03	0,81	0,0370	
		∑δi = 0,77		∑ Ri = 0,9505	
$1/\alpha_в$				0,1149	
$1/\alpha_н$				0,0435	
Thermal resistance of enclosing structure “on coats” R_o (m^{2}*ºC)/ W				1,1089	≥ 3,0786
Temperature of the inner surface, τint, ºC				15,23	≥ 10,7
Temperature drop t_0				4,77	≤ 4

Table 4: The results of normalized parameters calculation

	Thickness of the wall, in bricks				Normal value
	4	3,5	3	2,5	
Thermal resistance of enclosing structure “on coats”, Ro (m^{2}*ºC)/W	**1,6399**	**1,4670**	**1,2818**	**1,1089**	≥ 3,0786
Temperature of the inner surface, τint, ºC	16,78	16,40	15,87	15,23	≥ 10,7
Temperature difference Δt_0	3,22	3,60	**4,13**	**4,77**	≤ 4

The calculation results for other wall thicknesses are shown in Table 4.

The heat transfer performance uniformity factor if taken into account will increase the gap between the required value of the design thermal resistance of enclosing walls and the actual values obtained as a result of this calculation, as the calculated value of reduced thermal resistance R_o^r “on the façade”, with the window openings, is always less than the calculated heat transfer resistance of the wall R_o "on coats" without window openings (heat transfer performance uniformity factor r < 1). The heat transfer performance uniformity factor r for apartment buildings brick walls should not be less than 0.74, with the wall thickness of 510 mm, 0.69 with wall thickness of 640 mm and 0.64 with the wall thickness of 780 mm, respectively. As for the other two indicators, our calculations showed that condensation is not formed even at a minimum thickness of the brickwork of all mentioned above. A slight deviation from normal temperature difference between the interior temperature and the temperature of the enclosing structure inner surface is not critical for the comfortable indoor climate.

So, we can make a conclusion that even thick walls of historic buildings do not meet modern standards. It should also be mentioned that the historically-formed construction system has passed two century test of building operation, and it would be unwise to abandon it completely.

It should be noted that walling thermal requirements in Russia have been changed many times. A specific heating characteristic of brick apartment buildings of different years of construction, erected in accordance with the current standards of building heat insulation can be given as an example (Figure 2).

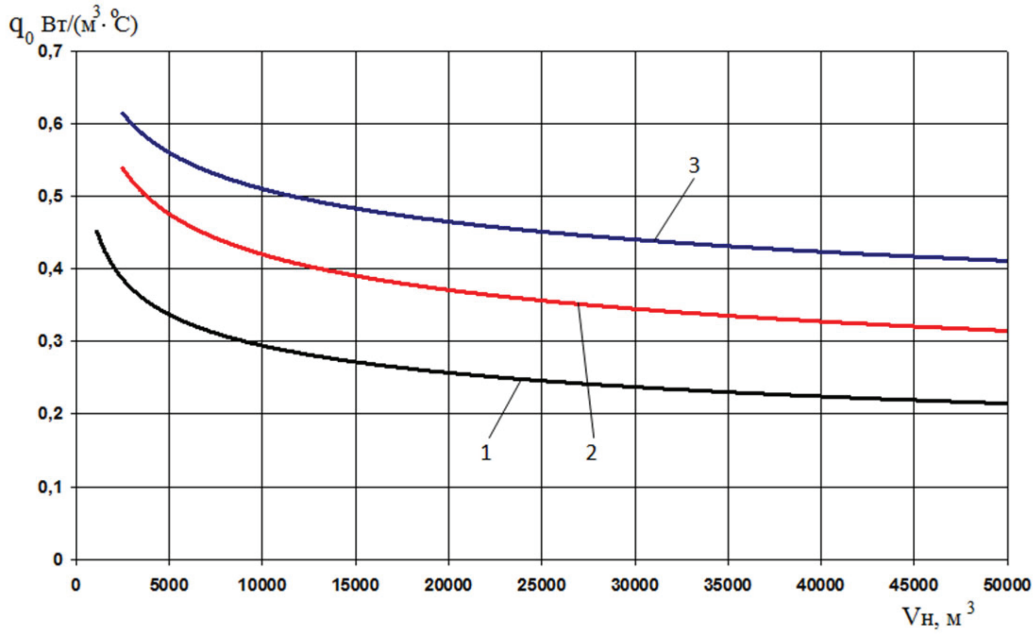


Figure 2:The relation between the specific characteristics of the building heating and the gross building volume: 1 - built before 1930; 2 - built in 1930 – 1958; 3 - built in 1958 - 1995.

$q_o=Q/[V_g(t_{int}-t_{ext})]$, W/(m^3 ^{0}C),

q_o – the specific characteristic of the building heating; W/(m3 ^{0}C) [07]; Q - heat flow of the building heating system, W; V_g - gross building volume, m3; tint - averaged over all quarters interior temperature, ^{0}C; text - design ambient air temperature for the cold season, ^{0}C [15].

As it follows from the data shown in Figure 2, the buildings erected before 1930 have the lowest thermal loads, with the requirements for building heat insulation at that period being quite low.

Since 1st September, 1995 buildings have been designed with increasingly high requirements for building heat insulation. Thus, the required thermal resistance for exterior walls was:

- Till 1st September, 1995 - 0,843 (m^2 • C/W);
- From 1st September, 1995 to 1st January, 2000,671 (m^2 • C/W);
- From 1st January, 2000 - 2,945 (m^2 • C/W);
- From 1st October, 2003 - 3,079 (m^2 • C/W)

To meet the building heat insulation requirements until 1995 it was enough to have 510 mm thickness of brickwork (2 bricks). Now, in order to achieve standard resistance heat of enclosing walls, corresponding to the value of 3.079 m^2•^{0}C/W it is necessary to have a uniform 1.69 m thickness of brickwork (a ceramic void brick with 1300 kg/m3 density on cement-sand mortar is taken for the calculation; thermal conductivity λ =0,58 W/(m•°C). The required thickness of brickwork should be enhanced taking into account the heat transfer performance uniformity factor.

Thus, we can conclude that according to current design building heat insulation standards in Russian, brickwork can not be regarded as an enclosing structure.

A graph showing the relation between the enclosing structure thermal resistance R_o and heat flow q passing through the building envelope is determined by the formula:

$q = (t_{int} - t_{ext})/R_0$, W/ m^2,

R_0 - thermal resistance to uniform brickwork structure (without heat-conducting inclusions), m²•°C / Watt (Figure. 3).

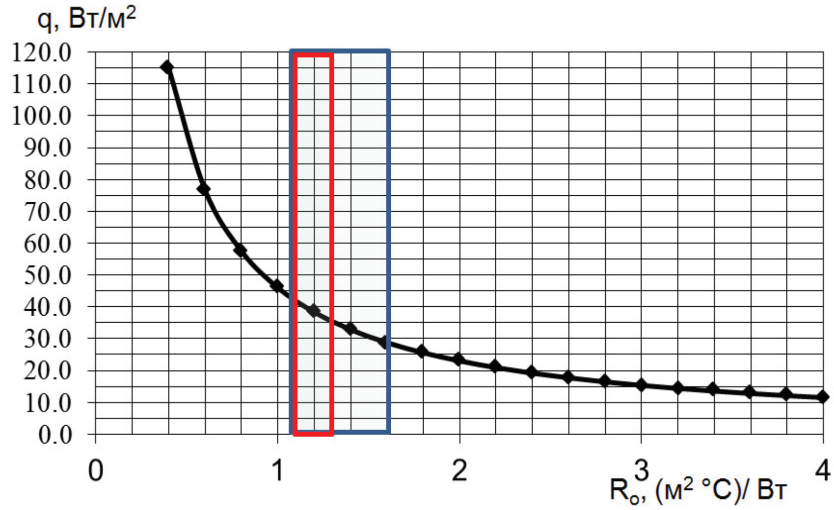


Figure 3: Graph of the relation between the enclosing structure thermal resistance Ro and heat flow q passing through the building envelope.

The relation has the hyperbolic shape. Typical thickness of the envelope walls (570-1150 mm) of historic buildings with matching values of the thermal resistance to the heat transfer (from 1.1 to 1.64) (m² ºC)/W (on the graph the area is highlighted with a blue rectangular) provides protection on the peak of the hyperbola. Further increase in the thickness of the brickwork would lead to a slight reduction of the heat flow. Such a conclusion favours the historically established thickness of the envelope walls.

It would be advisable to insulate only those constructions whose thermal resistance is lower than 1.32 m²•ºC/W, which is a sanitation requirement. On figure 4 the relevant area is highlighted with a red rectangular.

Nevertheless, thermal insulation is essential. The priority is given to the external thermal insulation.

However, the main disadvantage of such insulation is that it affects the historic appearance of a building.

Figure 4: Energy efficiency upgrade of the historic building in Nürnberg. The building before the upgrade and after. Ludwig-Feuerbach-Straße 75, 90489 Nürnberg, Germany

Even if the building is not on the statutory List of Buildings of Special Architectural or Historic Interest, this insulation leads to the loss of the visual historic environment [13, 32].

Figure 4 shows the older building before and after energy efficiency upgrading. Thermal insulation of the façade affected negatively the original historic appearance of the building [28].

It is unacceptable to lose the historic appearance of buildings because of regular changes in regulations for thermal protection of buildings.

In St.Petersburg the activity to conserve buildings of Special Architectural or Historic Interest combines techniques which are applied to constructions, environment and city planning. The overall city appearance, squares and streets of the historic centre are nationally protected along with the other heritage objects [19].

The buildings listed as of Special Architectural or Historic Interest are exempted from the Russian standards for thermal wall insulation. However, the decision about every building should be approved by governmental authorities. The same situation is in Finland and Norway [27]. Conservation of the traditional Russian wooden architectural monuments meets smoother requirements for thermal insulation. Nevertheless, there are a great number of traditionally constructed buildings which are not on the Protection List, but they are the ones which creates the visual concept of the historic buildings.

In spite of the priority of external thermal insulation for historic buildings, it can be more effective to use internal thermal insulation. The main obstacle of the internal thermal insulation - moisture condensation - can be removed by forming a vapour barrier [01, 7, 25].

Another obstacle of the internal thermal insulation is a possible contact of the effective insulator, with an inappropriate compliance with environmental standards, with the internal building environment. An excessive attention to the energy efficiency has clouded a more crucial problem - provision of healthy microclimate inside the building.

Most older buildings in St. Petersburg are protected as objects of Special Architectural or Historic Interest. Every building has its own particular components under protections. In most cases it is prohibited to alter decorative façades, but it is allowed to alter internal layouts in compliance with the Governmental Office which protects the cultural heritage objects [19].

However, if the decision about the thermal insulation is made, the internal façade can be insulated externally. Hereby the decorative façade shall be insulated from inside.

DISCUSSION

Weighing up all “pros” and “cons” for thermal insulation of historic buildings façades, it is necessary to draw attention to the loss of brickwork qualities as an envelope construction. The main quality of the brickwork is significant thermal inertia which allows to smooth temperature peaks inside the building.

Solar heat at the day time and slow heat emission into the inside space of the building during evening and night prevented buildings from overheating in summer time.

The problem of **summer protection from overheating** is not as crucial for St. Petersburg as the problem of thermal insulation. Historic buildings have massive walls, which means considerable thermal inertia. The window area is not large. This prevents the living space from overheating and keeps it cool at the dark time and in summer. This results from accumulating properties and considerable thermal inertia of the massive stone walls. In winter houses equipped with furnaces are heated only once or twice a day. The massive walls perform like heat accumulators. Thermal inertia of stone walls minimize cold bridging from doors and windows by making them insignificant. Internal insulation would break this energy interaction.

The historically established construction system is worth more careful attention. The study of its unique properties encourages to work out a complex of energy saving activities specially for historic buildings. The main construction fabric - sand-lime brick - is notably durable and environmentally friendly. Vapour-permeable sand-lime solutions and plasters contributed to maintaining healthy microclimate in dwellings.

External thermal insulation causes an unconditional energy loss because of impossibility to accumulate the solar energy by massive brick walls.

The usage of passive solar systems to increase energy efficiency is not greatly effective. A special placement of translucent and non-transparent building elements allows to control sun radiation flows and heat flows in dwellings. However, thermal energy accumulation requires massive construction elements. Thus the external thermal insulation obstructs the environment influence. In this case solar heating can never keep the thermal balance of the building [20].

Brick envelope is the most durable fabric. Moreover, this multilayer structure does not need repair and is not subject to damages. The service life of thermal insulation is long, 15-25 years. The increase in the resistance to heat transfer will undoubtedly cut heating costs, but at the same time it will lead to the costs of insulation production, installation, maintenance and disposal. Therefore the economic profit from the thermal insulation installation is slight.

Besides, thermal shield properties of the insulation construction will mostly depend on the quality of installation, lack of excessive moisture in the construction during its usage.The damp layer of insulation is affected by numerous temperature shifts over 0ºC, which reduces its service life [31].

Buildings with insulated walls suffer the highest heat losses from the uncontrollable ventilation. In order to reduce the heat losses it is necessary to draught-proof buildings and install controllable heat recovery ventilation.

Draught-proofing is one of the main principles in the Passive House concept and energy efficiency design and construction. The purpose of draught-proofing is the elimination of uncontrollable thermal energy leaks [06, 30, 02].

The changes in Russian regulations about air permeability for windows have been switching to draught-proofing since 70s, last century. Requirements of air permeability for windows changed in the following way:

- 1971 - 18 kg/ (m^2•h);
- 1979 - 10 kg/ (m^2•h);
- 1998 - 5 kg/ (m^2•h).

The natural ventilation system of multi-storey buildings is still traditionally based on air infiltration through cracks and gaps of windows. Therefore we can conclude that imposing tougher requirements of air permeability for windows has been the first step to draught-proofing, which has led to worsening microclimate with inappropriate air interchange [29].

In newly designed energy efficiency buildings draught-proofing is combined with the installation of controllable heat recovery ventilation. In older buildings energy efficiency reconstruction is usually started by occupants who replace their old windows, providing natural ventilation, with new draught-proofed ones. Hereby air interchange reduces, microclimate worsens and damp rises. In these conditions, if the temperature of the internal surface of the outer walls is not high enough, moisture can condense on this internal surface.

It is essential to switch from energy saving at all cost to microclimate improvement. One cannot save energy by risking life and health. The priority target of the contemporary construction is to form the appropriate climate in living spaces. Microclimate parameters are of energy nature and include: inside temperature, temperature of internal surface in envelope constructions, inside air quality (which also has energy content, as it is determined by ventilation air interchange) [29].

Microclimate improvement in living spaces, steady development of the society through the review of production fundamentals and energy consumption are different ways to the same goal. This goal is to provide healthy nation today and quality life for future generations.

Energy consumption of a building depends on both thermal and technological properties of envelope constructions and performance of heating and ventilation systems. Therefore it is necessary to focus on the reduction of energy consumption in these systems. Depreciation of equipment incomparably overtakes the service life of building constructions. This is the thing worth focusing. Relatively frequent changes of regulations for heat saving properties of envelope constructions reflect high growth rates of heating and climatisation technologies. Engineering equipment of a building is an integral part which can be upgraded without considerable financial expenses. The upgrade does not interfere with the constructive building structure and does not damage the visual historic environment.

CONCLUSION

The outcome of the research allows to make the following conclusions:

1) Energy efficiency upgrade of buildings requires a complex approach. The building is traditionally considered as a single energy system. The same systematic approach must be used to energy upgrade.

2) Insulation of envelope constructions, such as envelope walls, tend to be considered as one of

the main activities to increase energy efficiency in existing buildings. However, if it comes to historic buildings that the insulation of walls can be avoided, it is better to avoid it. The fact is that the loss of visual historic environment is incomparable in its importance with slight saving of energy resources.

In order to achieve the given standards it is better to focus on optimization of engineering equipment and production of energy in the building enclosure on the basis of renewable sources (solar or geothermal). In this case it is necessary to make calculations not by the given resistance to heat transfer in the building envelope constructions, but by an index of thermal energy consumption for heating a building.

3) It is feasible to protect not only the visual appearance of historic buildings, but historically established construction system.

4) It is necessary to assess the economic importance of planned activities aimed at insulating the envelope constructions in historic buildings, i.e. comparison of investments into energy saving and cost of saved energy. In addition, it makes sense to calculate the reduction of CO2 emissions resulted from the above-mentioned activities.

5) It is necessary to switch from energy saving at all cost to microclimate improvement. One cannot save energy by risking life and health.

SUMMARY

The dwelling sector consumes 40% energy and undoubtedly has to cut this consumption. However, the potential loss of the historic authenticity in St.Petersburg historic buildings resulting from the energy efficiency upgrade is as important as energy saving.

Therefore when it comes to historic buildings, it is better to focus not on thermal insulation of the envelope of walls, but on energy production based on renewable sources.

It makes sense to protect not only the visual historic environment , but historic construction system, which is unique, environmentally optimal and tested by century-long working experience.

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