SDG
JOURNAL OF LAW AND SUSTAINABLE DEVELOPMENT
ISSN: 2764-4170

SUSTAINABLE DEVELOPMENT OF THE CONSTRUCTION INDUSTRY THROUGH THE RATIONAL UTILIZATION OF AUTONOMOUS HEAT SUPPLY SOURCES BASED ON CLIMATE ZONING

[1]Kristina Filyushina, [2]Natalia Gusakova, [3]Yuri Bakrunov & [4]Elena Dyadkova

ABSTRACT

Objective: The objective of this research is to develop an integral approach for the efficient choice of space-planning and structural solutions for low-rise buildings using renewable energy sources for engineering systems during the full life cycle of the building, aimed at improving efficiency of capital investments, energy and resource conservation, and creating comfortable living conditions for the population while considering climatic zoning.

Method: The research used a theoretical and methodological approach to develop the foundations for the efficient choice of space-planning and structural solutions for low-rise buildings. The study utilized a comparative analysis of building materials and heat supply technologies to select the most appropriate options.

Results: The research showed that utilizing renewable energy sources for engineering systems during the full life cycle of a low-rise building can significantly reduce construction expenses while increasing availability of low-rise housing for certain categories of citizens. The developed integral approach allows for the most efficient choice of space-planning and structural solutions for low-rise buildings while taking into account climatic zoning.

Conclusions: The research provides a means of solving the problem of supplying citizens with low-rise housing with high level of comfort and quality. The results of the research can be used in implementation of regional strategic sectoral planning and public-private partnership projects' development. The developed integral approach allows for the rational utilization of autonomous heat supply sources in low-rise residential construction projects.

Keywords: Low-rise housing construction. Investment and construction project. Heat supply. Energy-efficient technologies.

Received: 09/09/2022
Accepted: 16/12/2022
DOI: https://doi.org/10.37497/sdgs.v11i1.263

[1] Tomsk State University of Architecture and Building, (Russia). E-mail: ke.filyushina@gmail.com
[2] Tomsk State University of Architecture and Building, (Russia). E-mail: n.v.gusakova@bk.ru
[3] National Research Moscow State University of Civil Engineering, (Russia). E-mail: y.o.bakrunov@mail.ru
[4] National Research Moscow State University of Civil Engineering, (Russia). E-mail: e.a.dyadkova@mail.ru

Filyushina, K., Gusakova, N., Bakrunov, Y., & Dyadkova, E. (2023). Sustainable development of the construction industry through the rational utilization of autonomous heat supply sources based on climate zoning. *Journal of Law and Sustainable Development*, *11*(1), e0231. https://doi.org/10.37497/sdgs.v11i1.263

DESENVOLVIMENTO SUSTENTÁVEL DA INDÚSTRIA DA CONSTRUÇÃO ATRAVÉS DA UTILIZAÇÃO RACIONAL DE FONTES AUTÔNOMAS DE FORNECIMENTO DE CALOR COM BASE NO ZONEAMENTO CLIMÁTICO

RESUMO

Objetivo: O objetivo desta pesquisa é desenvolver uma abordagem integral para a escolha eficiente de planejamento espacial e soluções estruturais para edifícios baixos usando fontes de energia renováveis para sistemas de engenharia durante todo o ciclo de vida do edifício, visando melhorar a eficiência de investimentos de capital, conservação de energia e recursos e criação de condições de vida confortáveis para a população, considerando o zoneamento climático.

Método: A pesquisa utilizou uma abordagem teórico-metodológica para desenvolver as bases para a escolha eficiente de soluções espaciais e estruturais para edifícios baixos. O estudo utilizou uma análise comparativa de materiais de construção e tecnologias de fornecimento de calor para selecionar as opções mais adequadas.

Resultados: A pesquisa mostrou que a utilização de fontes de energia renovável para sistemas de engenharia durante todo o ciclo de vida de um edifício baixo pode reduzir significativamente as despesas de construção, ao mesmo tempo em que aumenta a disponibilidade de moradias baixas para certas categorias de cidadãos. A abordagem integral desenvolvida permite a escolha mais eficiente de planejamento de espaço e soluções estruturais para edifícios baixos, levando em consideração o zoneamento climático.

Conclusões: A pesquisa fornece um meio para resolver o problema de fornecer aos cidadãos moradias baixas com alto nível de conforto e qualidade. Os resultados da pesquisa podem ser utilizados na implementação do planejamento estratégico setorial regional e no desenvolvimento de projetos de parceria público-privada. A abordagem integral desenvolvida permite a utilização racional de fontes autônomas de fornecimento de calor em projetos de construção residencial de baixo crescimento.

Palavras-chave: Construção de moradias baixas. Investimento e projeto de construção. Fornecimento de calor. Tecnologias de eficiência energética.

DESARROLLO SOSTENIBLE DE LA INDUSTRIA DE LA CONSTRUCCIÓN A TRAVÉS DE LA UTILIZACIÓN RACIONAL DE FUENTES AUTÓNOMAS DE SUMINISTRO DE CALOR EN BASE A LA ZONIFICACIÓN CLIMÁTICA

RESUMEN

Objetivo: El objetivo de esta investigación es desarrollar un enfoque integral para la elección eficiente de soluciones estructurales y de planificación espacial para edificios de baja altura utilizando fuentes de energía renovables para sistemas de ingeniería durante el ciclo de vida completo del edificio, con el objetivo de mejorar la eficiencia de inversiones de capital, conservación de energía y recursos, y creación de condiciones de vida confortables para la población considerando la zonificación climática.

Método: La investigación utilizó un enfoque teórico y metodológico para desarrollar las bases para la elección eficiente de soluciones estructurales y de planificación espacial para edificios de baja altura. El estudio utilizó un análisis comparativo de materiales de construcción y tecnologías de suministro de calor para seleccionar las opciones más adecuadas.

Resultados: La investigación mostró que el uso de fuentes de energía renovables para los sistemas de ingeniería durante el ciclo de vida completo de un edificio de poca altura puede reducir significativamente los gastos de construcción al mismo tiempo que aumenta la disponibilidad de viviendas de poca altura para ciertas categorías de ciudadanos. El enfoque integral desarrollado permite la elección más eficiente de soluciones estructurales y de planificación espacial para edificios de poca altura, teniendo en cuenta la zonificación climática.

Conclusiones: La investigación proporciona un medio para resolver el problema de dotar a los ciudadanos de viviendas de baja altura con un alto nivel de confort y calidad. Los resultados de la investigación pueden ser utilizados en la implementación de la planificación sectorial estratégica regional y el desarrollo de proyectos de asociación público-privada. El enfoque integral desarrollado permite la utilización racional de fuentes de suministro de calor autónomas en proyectos de construcción residencial de baja altura.

Palabras clave: Construcción de viviendas de baja altura. Proyecto de inversión y construcción. Suministro de calor. Tecnologías energéticamente eficientes.

INTRODUCTION

Right now the humanity possesses the greatest potential in the field of energy conservation and utilization of renewable energy sources. However, this potential is not always utilized, which leads to low efficiency of energy-saving technologies in construction consequently resulting in high prices of housing and utility services in the operation of buildings. This situation indicates the necessity to utilize autonomous heat supply sources in low-rise residential construction projects rationally taking climatic zoning into account.

To address this issue, the use of autonomous heat supply sources has become a viable solution for low-rise residential construction projects. By utilizing renewable energy sources and taking into account climatic zoning, these projects can provide comfortable and sustainable living conditions for citizens while reducing energy costs and carbon footprint.

However, the development and implementation of autonomous heat supply sources require an integral approach that considers various factors such as theoretical and methodological foundations, space-planning, structural solutions, building materials, and heat supply technologies. The use of renewable energy sources in construction should be carefully planned and executed to ensure the long-term efficiency of the system. Additionally, public-private partnerships and regional strategic sectoral planning can help in reducing construction expenses and increasing the availability of low-rise housing for citizens. Therefore, the development of an integral approach to the utilization of autonomous heat supply sources in low-rise residential construction projects can significantly contribute to the sustainable development of the construction industry and the provision of affordable housing for citizens.

LITERATURE REVIEW

Considerable attention in the works of domestic and foreign scientists is paid to the design and construction of low-rise residential buildings. In terms of main features of low-rise construction the works of Pokataev (2004), Agayants et al. (1991), Nanasova (2004), Telichenko, Terentyeva, Lapidus (2004), Perich (2006), Maksai (1979) were considered.

Foreign authors have studied the questions of implementation of investment and construction projects in various sectors of the economy quite extensively (O'Toole, 1997; Rhodes, Marsh, 1992). Their discoveries can also be applied to the Russian practice of low-rise housing construction (World Bank Group Private Sector Development Strategy..., 2003; Guidelines for Successful Public-Private Partnerships, 2003; Global Project Finance Yearbook, 2007). Studying the issues of energy conservation and energy efficiency improvement in low-rise housing construction in Russia the works of Beregovoy (2005) and Sheina (2008; 2013) were used, proposals of Egorov, Shprits and Nagmanov (2011) were considered for innovative ways of developing low-rise housing construction. For development of public-private partnership processes in low-rise construction the studies of such scientists as Larionov, Nezhnikova (2015), Larionov, Mishlanova (2014), Nikiforova (2007), Raikhman (2009), Chernov (2010), Vtornikova (2014), Korostin (2015), Lysenko (2015), Lysenko, Belyaev

(2011; 2015), Gasilov, Polshchikov, Serebryakova (2017), as well as the National Agency for Low-Rise and Cottage Construction (NAMIKS) were considered.

Based on available publications on the topic under consideration, it can be concluded that the issues of low-rise housing construction projects' development are of greatest relevance. To implement energy-efficient low-rise investment and construction project special attention should be paid not only to the choice of building materials, but also to the introduction of energy-efficient technologies (the use of energy-saving heating and water supply equipment) which will allow reducing heat losses of a low-rise building. The operational effect is to be achieved by means of savings on utility costs and on heating and hot water supply. According to these, we can consider external and internal effects. The external effect is the cost of maintaining heat sources in a low-rise building. The internal effect is the personal benefit of the owner due to savings on utility bills. It is essential to consider the achieved effects in more detail by conducting a comparative analysis of various systems of heating energy sources in a low-rise block-type building.

METHODS

To implement an energy-efficient investment and construction project in low-rise construction, it is necessary to select the source of heat supply for the low-rise building depending on the regional and climatic characteristics of the constructed object (centralized or independent (autonomous)). To do this, it is necessary to study the sources of thermal energy and main indicators by which it is possible to make a choice of an energy-efficient heat supply source for a low-rise building. The main sources of thermal energy include:

1. Autonomous boiler units:
– on solid fuel (firewood, coal, pellets, pyrolysis boilers);
– on gaseous fuel (traditional, gas-condensing);
– on liquid fuel;
– electric boilers.
2. Heat pumps.
3. Solar collectors.
4. Solar panels.
5. Wind generators.
6. Central heat supply.

To develop the method of selection of a house heat supply scheme, the following initial data is required for calculations:

1. Region of low-rise residential building construction.
2. Climatic features of the region:

Data according to SP 131.13330.2012:
– outdoor temperature of the coldest five-day period;
– average temperature of the heating period;
– duration of the heating period.
According to the scientific and applied reference book on climate of construction area:
– average annual wind speed;
– amount of scattered solar radiation;
– sum of total solar radiation;
– reflection coefficient (albedo) of the earth's surface and surrounding bodies;
– region's latitude.

The given indicators are the main and most important since it is necessary to take them into account while choosing the heat supply source for a low-rise building considering the influence of climatic characteristics.

To select autonomous boiler units, the following calculations are carried out:

– building heat losses;

– hot water supply thermal load.

The boiler unit installed in the building must ensure production of thermal energy that covers heat losses of the building and the cost of thermal energy for hot water supply water heating. Thus, the boiler capacity should be slightly higher than the sum of heat losses of the building and the cost of thermal energy for hot water supply water heating.

Assessment of the annual fuel consumption must be conducted for two periods: heating and non-heating. Therefore, when calculating fuel consumption, it is necessary to calculate the average consumption of thermal energy during the heating and non-heating periods.

During the heating period the building has:

– heat consumption for heating which depends on the outdoor temperature;

– heat consumption for hot water supply which depends on the temperature of the heated cold water.

During the non-heating period, the building has heat consumption only for hot water supply. To develop a method to calculate and select an autonomous boiler unit, we used most basic formulas (according to the methodology presented by Ph.D., Associate Professor Khutornoy (2016)). The calculation of these indicators is necessary for selection of the best heat supply source for a low-rise building (Table 1).

Table 1. Calculation and selection of an autonomous boiler unit

Indicators		Calculation formula	Symbols
1. Heating period	1.1. Heat consumption for heating (Gcal)	$Q_0^{h.per} = Q_{TL} \cdot 24 \frac{(t_a - t_{h.per})}{(t_{in} - t_o)} z_{h.per}$	Q_{TL}– calculated value of heating thermal load, Gcal/h (1 kW = 0.00086 Gcal/hour) t_{in} – average calculated value of air temperature inside heated buildings $t_{h.per}$– average temperature of the heating period with the average daily outdoor temperature ≤ 8 °C t_o – calculated value of the outdoor air temperature for heating design $Z_{h.per}$– duration of the heating period, days
	1.1.1. Calculated heat loss of the premises of a residential building is calculated by the heat balance equation (Gkal/h):	$Q_{hl} = Q_{ex} + \sum Q_{ad} + Q_{in} - Q_{hd}$	Q_{ex} – room heat losses through external enclosing structures, W $\sum Q_{ad}$ – total additional heat losses through building enclosing structures, W Q_{in} – heat loss due to infiltration, W Q_{hd} – household heat dissipation, W
	calculation of heat losses through external enclosing structures	$Q_{ex} = F \cdot k(t_{in} - t_o)n$	F – total area of enclosing structure, m^2 k – heat transfer coefficient of enclosing structure t_{in} – indoor air temperature t_o – air temperature of the coldest five-day period n – coefficient that takes into account location of enclosing structure in relation to outside air
	household heat input is determined by	$Q_h = 10 \cdot F_{ar}$	F_{ar} – floor area of heated room under consideration, m^2
	heat consumption for infiltrating air heating	$Q_{in} = 0.28 \cdot L \cdot p_{in} \cdot c(t_{in} - t_o)$	c – air heating capacity, 1 kJ/(kg·°C) L – exhaust air consumption, m^3/h, accepted for residential buildings equal to 3 m^3/h per 1 m^2 of the area of residential premises and kitchen, for administrative premises equal to 4 m^3/h per 1 m^2 of the area p_{in} – internal air density, kg/m^3, calculated by the formula $\rho_{in} = \frac{353}{273+t_{in}}$
	1.2. Heat consumption for hot water supply (Gkal)	$Q_{h.w}^{h.per} = m \cdot Q_h \cdot z_{h.per}$	Q_h – average hourly heat consumption for hot water supply, Gkal/hour (see Parag. 5) m – number of hours of hot water consumption per day, h
	1.2.1. Heat consumption for an average day	$Q_{t,m} = \frac{q_{t,m} \cdot \rho \cdot c(t_m^h - t^c)(1+\beta)}{24} \cdot 10^{-6}$	ρ – water density assumed to be equal to 1000 kg/m^3 c – specific water heat capacity, equal to 4.19 kJ/(kg·K) t_m^h – temperature of hot water at the point of water intake, assumed to be equal to 55 °C t^c – temperature of cold water assumed to be equal to 5 °C β – coefficient accepted for isolated water risers equal to 0.05–0.2, for non-isolated β = 0,1 – 0,3

2 Non - heating period	– hot water consumption on an average day (m³/day)	$q_{t,m} = \frac{q_{i,m} \cdot U}{1000}$	$q_{i,m}$ – rate of hot water consumption on an average day, litres, assumed to be equal to 105 litres
2 Non - heating period	Heat consumption for hot water supply (Gkal/h)	$Q_{h.w}^{n.hp} = m \cdot Q_h \frac{55 - t_s}{55 - t_w} L(350 - z_{h.p})$	L – coefficient that takes into account the reduction in the average hourly costs of hot water supply in the summer period in relation to the heating period (accepted to be L = 0.8) t_s, t_w – average summer and winter temperatures of cold water, respectively (accepted to be 15°C, 5°C respectively) 350 – number of days in hot water supply system operation year
3. Total amount of thermal energy consumed per year (Gkal)		$Q_p = Q_0^{hp} + Q_{h.w.}^{hp} + Q_{h.w.}^{n.hp}$	Q_o^{hp} – heat consumption for heating Q_{hw}^{hp} – heat consumption for hot water supply (during heating period) $Q_{h.w.}^{n.hp}$ – heat consumption for hot water supply (during non-heating period)
4. Annual fuel consumption (kg/year or m³/year)		$B_{fuel}^{year} = \frac{Q_p \cdot 10^6}{Q_{fuel} \cdot \eta_{b.u}}$	Q_{fuel} – calorific value of fuel, kcal/kg $\eta_{b.u}$ – boiler unit efficiency, proportion
5. Expenses on fuel for a 10-year period (except electric boiler) (RUB)		$Z_{fuel} = B_{fuel}^{year} \cdot C_{fuel} \cdot 10$	C_{fuel} – fuel cost for region, RUB/kg or RUB/m³
6. Expenses based on duration of boiler utilization and actual utility rates in the region (for electric boiler) (RUB)		$Z_{e.b} = Q_p \cdot T_e$	Q_p – total amount of thermal energy consumed per year, kW·h (1 Gkal = 1163 kW·h) T_e – electricity utility rate, RUB/kW·h

Source: compiled by the author based on Khutornoy, 2016; Khrustalev, 2008.

Calculations by formulas and data on the cost of boiler units are tabulated to identify the most cost-efficient source of thermal energy for construction of a low-rise house. To do this, the following methods can be distinguished on the basis of international and domestic practices:

1. The Borda count method – heat energy sources are ranked in descending order with the assignment of a rank value and then the total rank for each source is calculated.

2. The BOFa method – a comparative evaluation of options based on a variety of indicators.

Using these methods we will identify the most efficient source of heat supply for the construction of a low-rise block-type house, the following designations will be introduced for that:

A_{ji} – corresponding boiler unit with the number i according to the indicator with the number j;

W_{ji} – indicators necessary for selection of boiler unit with the number i for boiler unit with the number j;

R_{ji} – corresponding rank of boiler unit with the number *i* according to the indicator with the number *j*.

According to the Borda rule, variants of boiler units are then ranked by each indicator in descending order with the assignment of corresponding rank values to them (Table 2) and the total rank for each boiler unit is calculated $\sum_j^i A_{ji}$.

Table 2. Assigning ranks according to the Borda rule

Ranks	W_{ji}	…	W_{ji}
i	A_{ji}	…	A_{ji}
….	…	…	…
2	A_{12}	…	A_{1i}
1	A_{11}	…	A_{1i}

The choice of the boiler unit is determined by the maximum sum of the total rank $\sum_j^i A_{ji} \rightarrow$ max. To do this, an extra column is added in the ranking table of boiler units' technical and economic indicators, the values in which correspond to the rank of the row. Therefore, the boiler unit having the best value according to one of the indicators has the rank of 7, and the rank of 1 corresponds to the worst value. The best options are considered to be those boiler units that have gained the maximum sum of ranks. The further research is based on the identified options.

Further, in order to assess the remaining alternatives it is necessary to use the BOFa method, the essence of which is as follows:

1. Ranking of indicators necessary for selection of boiler unit (W_{ji}) (Table 3).

Table 3. Assigning ranks using the BOFa method

Rank (R_j)	Indicators (W_j)			
	W_1	W_2	…	W_n
	1	2	…	*n*

It follows from the table that the indicators are recorded in order of their importance, the most important being $W_1 = 1$, the next $W_2 = 2$ and so on.

2. Calculation of weight coefficients (V_j) for each *j*-th indicator:

$$V_j = 1 - \frac{R_j - 1}{N}\ ; j=1, N, \quad (1)$$

where N – the number of indicators required to select boiler unit.

3. Standardization of the obtained weight coefficients:

$$\tilde{V}_j = \frac{V_j}{\sum_{m=1}^{N} V_m}. \quad (2)$$

4. Normalization of the indicators essential for selection of boiler unit, in accordance with the conditions of the maximum or minimum of each of the considered indicators and compilation of a table of normalized values of the indicators (Table 4).

Normalization to the maximum and minimum of indicators is calculated by the following formulas:

$$H_{\max} = \frac{A_{ij}}{A_{\max}}, \quad (3)$$

$$H_{\min} = 1 - \frac{A_{ij}}{A_{\max}}. \quad (4)$$

Table 4. Normalized values of indicators according to the Borda rule

Boiler unit	Indicators		
	N_{ji}	…	N_{ji}
A_n	N_{ji}	…	N_{ji}
….	…	…	…
A_2	N_{12}	…	N_{1i}
A_1	N_{11}	…	N_{1i}
V	V_1	…	V_{1i}
Normalization condition	max / min	max / min	max / min

5. Calculation of values of the generalized indicator $\overline{W}_j$ for each heat supply source:

$$\overline{W}_j = \sum_{j=1}^{N} \hat{V}_{ij}, \quad (5)$$

$$\hat{V}_{ij} = \tilde{V}_j \cdot V_{ij}, \quad (6)$$

$$\overline{W}_j \to \max. \quad (7)$$

The results of calculating the values of generalized indicators for each individual unit are summarized in the final Table 5.

Table 5. The results of calculating the values of generalized indicators for each individual unit

N_i	N_1	…	N_n
$\overline{W}_i$	$\overline{W}_1$	…	$\overline{W}_n$

The presented method allows making a choice of equipment for the most efficient heat supply of a low-rise house according to the criteria of the best result (Speshilova, Shibneva, 2015; Filyushina et al., 2019).

RESULTS AND DISCUSSION

Afterwards, the most efficient source of heat supply for a low-rise house (for example, a low-rise house in Tomsk) is chosen. The choice is based on the previously presented method of selection of energy-efficient sources of heat supply for a low-rise building.

To assess the annual heat and fuel consumption, as well as to select the most efficient boiler unit Table 6 is compiled.

Table 6. Assessment of annual heat and fuel consumption for the city of Tomsk, Russia

Indicators	Calculation of main indicators
1. Heat consumption for heating (Gcal)	$Q_{o}^{year}=Q_{o}^{hour}\cdot 24\frac{(t_{j}-t_{or})}{(t_{j}-t_{o})}n_{h.p}=0.007\cdot 24\frac{(22+3.9)}{(22+30)}219=18.3\ \frac{Gcal}{year}$
2. Heat consumption for hot water supply (Gcal)	$Q_{c.w.}=m\cdot Q_{av.c.w}\cdot n+m\cdot Q_{av.h.w}\frac{55-t_{s}}{55-t_{w}}L(350-n)=8\cdot 0.001\cdot 219+8\cdot 0.001\times$ $\times\frac{55-15}{55-5}0.8(350-219)=2.4\ \frac{Gcal}{year}$
2.1. Heat consumption for an average day	$Q_{t,m}=\frac{0.42\cdot 1000\cdot 4.186(55-5)(1+0.1)}{24}=4029.03\ kJ/h=1.12\ kW$
Hot water consumption on an average day (m^3/day)	$q_{m,м}=\frac{105\cdot 4}{1000}=0.42\ m^{3}/day$
3. Total amount of thermal energy consumed per year (Gcal)	$Q_{p}=Q_{o}^{year}+Q_{h.w}=18.3+2.4=20.7\ \frac{Gcal}{year}$

Source: compiled by the author based on Khutornoy, 2016; Khrustalev, 2008.

Further, it is necessary to make the choice of heating boilers out of the following types: electric, gas-condensing, oil-fired, wood-fired, coal-fired, pyrolysis and pellet ones according to the presented list of autonomous boiler units for a low-rise block-type house. Based on the calculation data of heat losses of the building and thermal load of hot water supply for a low-rise house in Tomsk, as well as its operational characteristics and operating costs, the most rational and economically feasible heating boiler for a low-rise house is selected. The results are given in Table 7.

Table 7. Comparative technical and economic analysis of boiler units

Boiler unit	Fuel	Efficiency coefficient	Lowest calorific value of fuel, kcal/kg	Annual fuel consumption, kW/ m^3/kg	Cost per unit of fuel, RUB/kW/m^3/kg	Fuel costs, kRUB.	Expenses on purchasing boiler unit, kRUB	Operating costs, kRUB	Total operating cost, kRUB/year
Electric boiler RODA Strom SL 15	Electrical energy	98	–	23592.6	3.89	91.8	30	4.5	126.3
Gas-condensing boiler DELFIS CONDENSING KRB 12	Gas	97.1	8200	2599.8	7.43	19.3	65	19.5	103.8
Oil-fired boiler Lamborghini EXA 20	Fuel oil	89.9	9800	2349.5	8.5	20	25	11.3	56.2
Wood-fired boiler EnergyWood 12	Fire wood	85	3500	6958	6.5	45.2	55	24.8	125
Coal-fired boiler BURAN TECH-15	Coal	88	5500	4276.9	5.1	21.8	45	20.3	87.1
Pyrolysis boiler Cot Eco Uta 15	Fire wood	90	3500	6571.4	6.5	42.7	37	13	92.7
Pellet boiler EKOGREN EG-PELLE EG–15	Fuel pellets	91	4150	5481.3	5.5	30.1	165	57.8	252.9

Source: compiled by the author based on Khutornoy, 2016; Khrustalev, 2008.

Based on the conducted comparative technical and economic analysis, the following conclusions can be drawn:

– the most cost-effective is the oil-fired boiler;
– the most expensive boiler unit is the pellet boiler;
– the most expensive boiler in operation is the pellet boiler;
– the electric boiler has the highest fuel costs.

Taking into account the features of the facility for which the heating system is being developed, it is advisable to mathematically assess dependence of all indicators and determine the most efficient boiler unit. To do this, the Borda count rule is used (Table 8).

Table 8. Ranking of boiler units for a low-rise house

Boiler unit		Ranks	Efficiency coefficient	Lowest calorific value of fuel, kcal/kg	Annual fuel consumption, kW/ m3/kg	Cost per unit of fuel, RUB/kW/m3/kg	Fuel costs, kRUB.	Expenses on purchasing boiler unit, kRUB.	Operating costs, kRUB.	Total operating cost, kRUB/year
A	Electric boiler	7	A	C	C	A	B	C	A	C
B	Gas-condensing boiler	6	B	B	B	E	C	A	C	E
C	Oil-fired boiler	5	G	E	E	G	E	F	F	F
D	Wood-fired boiler	4	F	G	G	D	G	E	B	B
E	Coal-fired boiler	3	C	D	F	F	F	G	E	D
F	Pyrolysis boiler	2	E	F	G	B	G	B	D	A
G	Pellet boiler	1	G	A	A	C	A	G	G	G

Next, table of ranks for all boiler units is compiled (Table 9 and Figure 1).

Table 9. Ranks of boiler units

Boiler unit	Efficiency coefficient	Lowest calorific value of fuel, kcal/kg	Annual fuel consumption, kW/ m^3/kg	Cost per unit of fuel, RUB/kW/m^3/kg	Fuel costs, kRUB.	Expenses on purchasing boiler unit, kRUB.	Operating costs, kRUB.	Total operating cost, kRUB/year	Sum of ranks
A	7	5	5	7	6	5	7	5	47
B	6	6	6	3	5	7	5	3	41
C	1	3	3	1	3	2	2	2	17
D	2	1	1	4	1	3	6	6	24
E	5	4	2	2	2	4	3	4	26
F	3	2	4	6	4	6	4	7	36
G	4	7	7	5	7	1	1	1	33

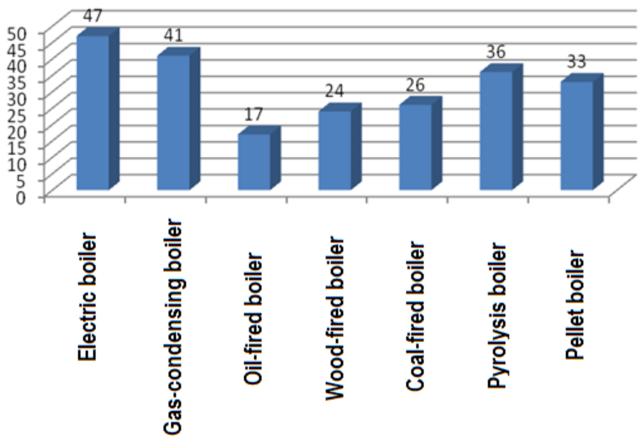

Figure 1. Choosing the most efficient source of heat supply for a low-rise building in Tomsk using the Borda rule

According to the Borda rule the best options when choosing a source of heat supply for a low-rise house are the options with the biggest sum of ranks. The electric boiler has the biggest sum in all indicators (the value of the total rank is 47), next is the gas-condensing boiler and the pyrolysis boiler (the values of the total rank are 41 and 36, respectively). The given 3 types of boiler units are the most efficient for the city of Tomsk.

To determine which heat supply source will be used in the low-rise building, we will apply the BOFa method which means we will rank the indicators necessary for choosing boiler unit by degree of importance, calculate the weight coefficient and normalize it, the values of obtained indicators are summarized in Table 10.

Table 10. Ranking of indicators necessary for selection of boiler unit by degree of importance, calculation of weight coefficients and their normalization

Indicators	Efficiency coefficient	Lowest calorific value of fuel, kcal/kg	Annual fuel consumption, kW/m^3/kg	Cost per unit of fuel, RUB/kW/m^3/kg	Fuel costs, kRUB.	Expenses on purchasing boiler unit, kRUB.	Operating costs, kRUB.	Total operating cost, kRUB/year
Rank	7	8	6	4	5	1	3	2
Weight coefficient	0.25	0.13	0.38	0.63	0.50	1.00	0.75	0.88
Rationing	0.06	0.03	0.08	0.14	0.11	0.22	0.17	0.19

Next, we will normalize the three boiler units in accordance with the conditions of the maximum or minimum of each of the considered indicators and compile a table of normalized values of the indicators (Table 11). Next, we will calculate the values of the generalized indicator for each heat supply source and present them in Figure 2.

Table 11. Normalized values of indicators required for the selection of a boiler unit

Boiler unit	Efficiency coefficient	Lower calorific value of fuel, kcal/kg	Annual fuel consumption, kW/m^3/kg	Cost per unit of fuel, RUB/kW/m^3/kg	Fuel costs, kRUB.	Expenses on purchasing boiler unit, kRUB.	Operating costs, kRUB.	Total operating cost, kRUB/year
Electric boiler	1.00	0.00	1.00	0.48	1.00	0.54	0.77	1.00
Gas-condensing boiler	0.99	1.00	0.89	1.00	0.79	1.00	1.00	0.18
Pyrolysis boiler	0.92	0.43	0.72	0.13	0.53	0.43	0.33	0.27
Normalization	max	max	min	min	min	min	min	min

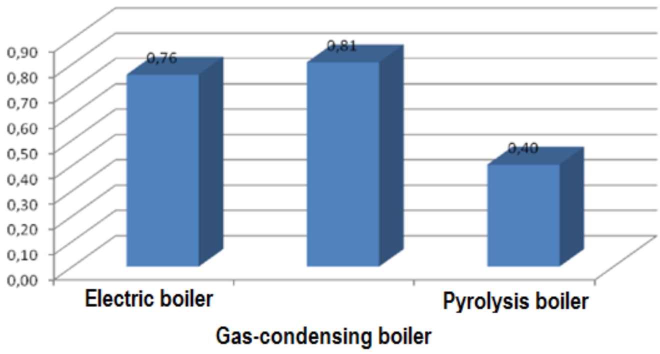

Figure 2. Generalized indicator's calculation results for each heat supply source

According to the conducted calculations the gas-condensing boiler is selected as a basic heat supply option for the low-rise building in Tomsk. We compared it with other alternative heat supply sources (Table 12).

Table 12. Comparison of alternative sources of thermal energy with the selected option (gas-condensing boiler)

Indicators	Parameters	Notice	Calculation	Conclusion
1. Solar energy	Solar energy, kWh/m^2: 2500 2000 1500 1000 500	Solar collectors can be used in case solar energy is 1500 – 2500 kWh/m^2	Power consumed by solar collectors – 1.28 kW Annual electricity expenses in case of solar collectors' utilization – 26,7 kRUB/year	Utilization of a collector is a costly option for Tomsk region and the pay-off period is 7.4 years, while it should also be taken into account that a system with a solar collector does not cover demand for the heating load
2.Air temperature of the coldest five-day period	Air temperature of the coldest five-day period, °C least severe weather conditions: –25, –38; severe conditions: –38, –51; most severe conditions: –47, –62	Heat pumps can be used only under the least severe air conditions	Annual operating costs: heat pump 150,5 kRUB; gas-condensing boiler 103,8 kRUB.	Heat supply of a low-rise building by means of a heat pump is a more expensive option for Tomsk compared to a gas-condensing boiler
3. Wind speed	Wind speed, m/sec: 1–3 3–4 4–5 5–6 6–7 more than 7	The most efficient option is to use wind generators at the highest speed of wind	Power consumed by wind generator – 1.8 kW. Annual electricity expenses in case of wind generator utilization – 37,6 kRUB/year	Wind generator utilization is a costly option for the city of Tomsk, and the pay-off period is 4.25 years.

Source: compiled by the author based on Khutornoy, 2016.

The given method of selection of a heat supply for a low-rise building can be used in other regions and optimized by substituting climatic characteristics of each individual locality (Gusakova et al., 2018a; 2018; Gusakova, Filyushina, 2018).

The final stage is to compare efficiency of utilizing centralized and decentralized heat supply sources in a low-rise building. To do this, we will analyze utility expenses for a low-rise block-type house with an autonomous heating system and total area of heated premises of 100 m^2 and utility expenses for an apartment of 83 m^2 with a central heating system.

An autonomous heat supply source for a low-rise house is installed inside the block-type house. The installation cost is quite high and usually amounts to 30% of the equipment cost but it is compensated by reducing operating costs. At the same time, it is worth mentioning that for this money the owner of the block-type house gets heating, hot water supply and air conditioning. It means that the owner will not experience any pre-planned or emergency shutdowns of hot water for a month in the summer and the recovery system carrying out climate control of each room in the house will not allow overheating while residents of regular houses open vent panes and windows, trying to escape from the heat in the spring, or turn on additional heating devices in the autumn (Table 13).

Table 13. Comparison of utility bills of a low-rise block-type house with an autonomous heating system and an apartment with a central heating system in Tomsk

Indicators	Values
1. Area of the 1st block in a low-rise block-type house, m^2	100
Cost of heating per year, RUB / cost of heating per 1 m^2, RUB	
electric boiler	91800 / 918
gas condensing boiler	19300 / 193
oil-fired boiler	20000 / 200
wood-fired boiler	45200 / 452
coal-fired boiler	21800 / 218
pyrolysis boiler	42700 / 427
pellet boiler	30100 / 301
2. Total area of apartment, m^2	83
2.1 Cost of heating per month, RUB	4800
2.2 Cost of heating per year, RUB	38400
2.3 Cost of heating per 1m^2, RUB	462.65
3. Savings from utilization of an autonomous heat supply system per year, RUB:	
electric boiler	– 53400
gas condensing boiler	19100
oil-fired boiler	18400
wood-fired boiler	– 6800
coal-fired boiler	16600
pyrolysis boiler	– 4300
pellet boiler	8300

Analyzing the given table, it can be concluded that according to the presented method of selection of heat supply sources at the last stage of the analysis the gas-condensing boiler was chosen as a basic source of heat supply due to the fact that by means of it annual utility bills are reduced by 19,100 rubles. The other two sources (the electric and pyrolysis boilers) increase utility bills by 53,400 rubles and 4,300 rubles per year, respectively, which proves efficiency of the proposed method and possibility of its application during selection of the best source of heat supply in any region during construction of a low-rise building.

CONCLUSIONS

According to the results of the research, the following conclusion can be drawn: the gas-condensing boiler is an efficient replacement for central heating, heat pumps, solar panels, wind generator, pyrolysis boiler and electric heating in Tomsk. The advantages of the gas-condensing boiler over other sources of heat supply are undeniable.

Therefore, it is essential to ensure that the installation and operation of gas-condensing boilers in Tomsk comply with all relevant environmental laws and regulations, including emissions standards and regulations related to the production and transportation of natural gas. Furthermore, sustainable development principles should be taken into account in the design and implementation of heating systems, such as the use of renewable energy sources and energy-efficient technologies.

In this regard, legal and policy measures can play a significant role in promoting the use of environmentally friendly and sustainable heating systems, such as providing incentives for the installation of renewable energy systems, setting emissions standards and regulations for heating systems, and promoting energy efficiency measures. By incorporating sustainability principles into the legal framework and promoting the use of environmentally friendly heating systems, Tomsk can contribute to the global efforts to address climate change and promote sustainable development.

REFERENCES

Agayants, L.M., Masyutin, V.M., Bochkareva, N.V., Ryabchenko Yu.V., Savina, L.P. (1991). Residential house for an individual developer. Moscow: Stroyizdat.

Beregovoy, A. M. (2005). Buildings with energy-saving structures: dissertation of PhD in Technical Sciences. Penza.

Chernov, A.V. (2010). Public-private partnership in the field of low-rise housing construction. Law and investments, 4, 39-42.

Egorov, A. N., Shprits, M. L., & Nagmanova, A. N. (2011). Innovativeness in the construction sector of the economy as a tool for minimizing cost, reducing time and improving the quality of construction. Issues of modern economics, (3).

Filyushina, K.E., Khutornoy, A.N., Yarushkina, N.A., Astafiev, S.A., Yarlakabov, A.A. (2019). Development of a method for the most efficient heat supply selection for a low-rise building. Economics and entrepreneurship, 6(107), 1014-1021.

Gasilov, V. V., Polshchikov, D. V., & Serebryakova, E. A. (2017). Risk evaluation of the state, municipal, private investors and tenants in public-private partnership projects. FES: Finance. Economy, 3, 47-51.

Global Project Finance Yearbook. (2007). New York: The McGraw-Hill Companies, Standard & Poor's. Retrieved from: http://business-panels.ru/1276007279.pdf

Guidelines for Successful Public-Private Partnerships. (2003). European Commission. Retrieved from: https://ppp.gov.ie/wp/files/documents/guidance/other_guidance/EU-Guidelines-for-Successful-PPP.pdf

Gusakova, N. V., & Filyushina, K. E. (2018). Application of a method for the most efficient space-planning and structural solutions selection for low-rise buildings. Bulletin of Tomsk State University of Architecture and Building, 20(3), 71-85.

Gusakova, N. V., Filyushina, K. E., & Yarlakabov, A. A. (2018a). Innovative technologies of energy supply of low-rise settlements in investment projects of low-rise construction. In Topical problems of innovative development of nuclear technologies. Scientific session of the NRNU MEPhI: conference materials (pp. 161).

Gusakova, N. V., Filyushina, K. E., & Yarlakabov, A. A. (2018b). Investigation of energy efficiency of heat supply sources in low-rise construction. Bulletin of Tomsk State University of Architecture and Civil Engineering, 20(6), 160-166.

Khrustalev, B. M. (Ed.). (2008). Heat supply and ventilation. Course and graduation projects' development. Moscow: Publishing House of ASC.

Khutornoy, A. N. (2016). Boiler installations: A textbook with the label of AMA. Tomsk: Publishing house of Tomsk State University of Architecture and Building.

Korostin, S.A. (2015). Public-private partnership as an effective mechanism for solving the housing issue in the regions. Regional problems of economic transformation, 2(52), 41-45.

Larionov, A.N., Mishlanova, M.Yu. (2014). Development of "construction – living environment" ecological and economic system: monograph. Moscow: MGSU.

Larionov, A.N., Nezhnikova, E.V. (2015). Evaluation of attractiveness of housing construction objects for the end customer by the method of hierarchy analysis. Real estate: economics, management, 1, 20-22.

Lysenko, A.V. (2015). Development of economic mechanism for implementation of innovative projects (on the example of low-rise housing construction): dissertation. Volgograd.

Lysenko, A.V., & Belyaev, M.K. (2010). Can we expect innovative development of the construction industry? In: Science and education: architecture, urban planning and construction: materials of the International conference dedicated to 80th Anniversary of construction education and 40th Anniversary of architectural education of Volgograd region (pp. 187-190). Volgograd: VolgGASU.

Lysenko, A.V., & Belyaev, M.K. (2011). Low-rise housing construction - solution of numerous problems. In: Scientific potential of young scientists for innovative development of the construction complex of the Lower Volga region: materials of the International scientific-practical conference (pp. 128-132). Volgograd: VolgGASU.

Maksai, D. (1979). Designing residential buildings. Moscow: Stroyizdat.

Nanasova, S.M. (2004). Constructions of low-rise residential buildings. Moscow: ACB.

Nikiforova, M.E. (2007). Methodological approaches to organizational and economic development of ecological housing construction: dissertation. Volgograd.

O'Toole, L. (1997). The Implications for Democracy in a Networked Bureaucratic World. Journal of Public Administration Research and Theory, 7.

Perich, A.I. (2006). On the problem of construction of mobile buildings from light-weight structures. Industrial and civil engineering, 1, 45-46.

Pokataev, V.P., Tokarev, A.A. (2004). Structural types of low-rise buildings (individual houses, cottages, dachas). Retrieved from http://nnm-club.name/forum/viewtopic.php?t=790865

Raikhman, V.A. (2009). Creation of economic strategy for the development of low-rise housing construction in Russia: dissertation. Moscow.

Rhodes, R., Marsh, D. (1992). Policy Network in British Politics. A Critique of Existing Approaches, in: Policy Network in British Government. Oxford: Oxford Academic.

Sheina, S. G. (2008). Methodology of strategic management of technical condition of housing stock by modeling and optimizing organizational and technological solutions: dissertation of PhD in Technical Sciences. Rostov-on-Don.

Sheina, S. G., & Minenko, E. N. (2013). Development of an optimization model for choosing energy-efficient solutions in low-rise construction. Rostov-on-Don: Rostov State University of Building and Construction.

Speshilova, N. V., & Shibneva, A. Yu. (2015). Application of mathematical methods to assessment of efficiency of the Orenburg region's agro-industrial complex investment. Naukovedenie, 7(6). Retrieved from http://naukovedenie.ru/PDF/54EVN615.pdf

Telichenko, V.I., Terentyev, O.M., Lapidus, A.A. (2004). Technology of construction of buildings and structures: textbook for building universities. Moscow: Vysshaya Shkola.

Vtornikova, Ya.E. (2014). Public-private partnership in the field of low-rise housing construction. Scientific Bulletin of the Voronezh State University of Architecture and Civil Engineering, 6, 73-79.

World Bank Group Private Sector Development Strategy: Implementation Progress Report. (2003). Washington, D.C. Retrieved from: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/322041468164040279/world-bank-group-private-sector-development-strategy-implementation-progress-report