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Article

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Modeling Energy-Efficient Consumption at Industrial Enterprises

Georgi N. Todorov[1]*, Elena E. Volkova[2], Andrey I. Vlasov[3], Natalya I. Nikitina[4]

[1]Varna Scientific Institute of the Eastern European Commonwealth - VSIEEC, Bulgaria, [2]Tyumen Industrial University, Russian Federation, Russia, [3]Bauman Moscow State Technical University, Russian Federation, Russia, [4]Russian State Social University, Russian Federation; Pirogov Russian National Research Medical University (RNRMU), Russian Federation, Russia.
*Email: todorov.g@protonmail.com

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ABSTRACT

A possibility to reduce costs incurred in both product manufacturing and energy consumption constitutes energy-efficient consumption at industrial enterprises. Manufacturers operating in various economic sectors adopt similar conceptual models of energy consumption, which allows developing a universal solution for modeling such processes. The central problem of modeling lies in finding an adequate objective function based on a sufficient set of parameters and characteristics of the efficiency of an enterprise's power circuit. The article justifies the performance indicators of industrial enterprises' power supply systems. The literature review proves that economic feasibility of energy efficiency is especially obvious if a massive modernization program is implemented. The estimates produced indicate that the largest portion of the potential energy savings is attributed to implementation of energy-saving projects in industrial buildings and other structures. We present a mathematical model designed to perform a comparative analysis of technical and economic features of two modernization scenarios of the heat and power supply system of an industrial enterprise circuit. Performing a simulation calculation based on performance aspects of Russian companies, the paper outlines the advantages of integrated modernization and analyzes the influence of various factors. The results reveal that there is an inverse correlation between specific heat consumption of buildings under thermal modernization and the length of the thermal network. As specific energy consumption in the thermal modernization scenario increases, the payback period for capital investments decreases. The effect of this dynamics is virtually proportional. Compared with total costs for various heat sources, the share of capital costs differs significantly; however, the share of running costs is dominant for all types of units. At the same time, the length of an enterprise's heat circuit weakly affects the payback period of capital costs.

Keywords: Energy Efficiency, Industrial Enterprise, Thermal Modernization, Energy Modeling
JEL Classifications: Q43, L95, L97

1. INTRODUCTION

Today's significant rise in energy consumption results from rapid economic development (Dakwalea, et al., 2011; Patterson, 1996). This may place an elevated pressure on the industrial production system and attract special attention to the efficient use of energy resources that are beyond reasonable doubt the main driving force of any economic activity (Alam, 2006; Reynolds, 1994). The interdependence between the electric power industry and economy is gradually strengthening and projected onto the social sphere what is confirmed by consistent patterns (Golovanova, 2009). Consequently, economic development management is efficient only if energy flows are taken into account during the manufacturing process. At that, enhancing energy efficiency should be the core factor in modernization.

The structure of production and specific climatic conditions make searching for ways of energy-efficient consumption more relevant.

In this context, the characteristic examples are the heating systems of Russia, Finland, Norway and Canada. If developed countries have long been oriented towards the energy efficiency strategy, for Russia this trend is only gaining momentum. High energy intensity of production processes and the irrational use of energy resources are among the topical problems for enterprises operating in various sectors of the Russian industry (Mastepanov, 2009). The primary reasons behind low energy efficiency of industrial enterprises infrastructure are the following (Borgolova et al., 2013): Significant physical and moral depreciation of fixed assets and, as a result, high accident incidence rate of equipment; poor monitoring, control and regulation of energy resources consumption; increased losses in production processes and high flow of primary fuel and energy resources; lack of skilled specialists in the field of energy management, etc. Energy and economic problems are predetermined by the specificity of a particular region and how well it is provided with energy development resources (Tishkov, Scherbak, 2015).

While the task of improving energy efficiency of modern production is becoming more urgent, it is necessary to analyze the specific character of energy consumption in more detail. According to empirical studies, economic feasibility of works aimed at increasing energy efficiency of industrial enterprises' buildings and structures is most obvious if a large-scale reconstruction is being performed (Kolegov et al., 2012: Gashin and Grishkina, 2017). The extensive literature on this topic (Edelev and Tatuev, 2013) typically addresses technical re-equipment of production and increasing labor productivity as the major aspects of industrial development. At the same time, there is insufficient research on improving manufacturing energy efficiency. Given that the industrial sector consumes the largest portion of energy resources and accumulates energy-intensive production, the issue of energy conservation and costs reduction is of special importance.

This problem is impossible to tackle without well-grounded efficiency parameters of enterprises' heat and power supply systems. However, the current literature abounds with such parameters and ways for enhancing energy efficiency, which impedes their practical application. Thus, the present research aims to model energy efficiency of industrial enterprises.

2. LITERATURE REVIEW

Numerous researchers argue that the electric power industry is the main indicator of the socio-economic system stimulating economic development (Coccia, 2010). Today's global trends in the development of the electric power industry are aimed at solving a number of conceptual problems (Akulova, 2014): First, to provide energy supply (energy supply continuity); second, to ensure energy availability (in terms of price and energy conservation) and, third, energy acceptability (minimal effect on the environment).

The issues of rational consumption of fuel and energy resources are widely debated today. The dynamics of energy conservation is described by the intensity of energy resources use (Golovanova et al., 2014; Arvanitis and Ley, 2013). Energy conservation refers to the implementation of energy-saving measures aimed at increasing the efficiency of energy resources, electrical and heat power. Energy efficiency is regarded as a technically feasible and economically viable quality of using energy resources and power at the current level of technological development (Efremov and Markman, 2007).

The energy saving indicator is commonly interpreted as a qualitative and/or quantitative characteristic of energy-saving measures being designed or implemented. Activities in the field of energy conservation are described by such indicators as the amount of actual saving of fuel and energy resources, loss reduction (in particular, due to optimization of operating parameters of energy consumption (Villar et al., 2007), and also a decrease in energy intensity.

Within the framework of the classical theory of sociotechnical systems, decreasing energy intensity of economy is traditionally attributed to various factors of technological progress, such as R&D, technology acquisition (Shan et al., 2012), technology spillover effect (Verdolini and Bosetti, 2017), etc., (Slavianov, 2011; Hinloopen, 2000, 2001; Lei et al., 2012; Romer, 1990; Tanaka, 2011). A number of model studies on the factors behind energy intensity reduction (e.g. the case of Russia is investigated by Ratner (2014) examine how domestic R&D and one of the possible channels for technology spillover - foreign direct investment - influence energy intensity. It is shown that domestic research and development projects produce a more remarkable reduction in energy intensity, as compared with foreign investment.

The versatility of energy conservation results from its structure by type of energy resources, stages of the fuel and energy balance, economic spheres, as well as technological processes. To achieve a long-term sustainable growth, it is necessary to comprehend the structure and distinguishing features of conservation (Strielkowski et al., 2017). For this reason, systemic studying of the core factors affecting this process is required, first of all, to take decisions on saving energy carriers during production. To explore the influence of technological progress on industrial energy intensity, times series of the following indicators are applied: Overall costs involved in technological innovation; costs incurred in purchasing machinery and equipment; technology acquisition costs; software acquisition costs (Khrustalev and Ratner, 2015); expenditure on research and development of new products, services and production methods (Gavrilescu, et al., 2018); staff training costs (Khrustalev and Larin, 2011; Golove and Eto, 1996).

In the literature, there is an additional opportunity provided to structure and determine the qualitative features of the parameters for reducing energy intensity of a product, but in most cases, the evaluation is made only with respect to reducing the overall costs providing no opportunity to analyze the impact on the entire production cycle. A number of researchers believe that in the circumstances of a possible change of energy sources (Dezellus et al., 2015), the production cycle should be identified, which is a quite complicated task for some plants. Given that production can be subjected to modernization quite often, this viewpoint requires a more flexible approach to be implemented in the sphere of energy consumption. Modernization issues are typically considered separately from the problems of energy-efficient modernization (Osiński and Grudzień, 2019). At that, from a technical perspective, they should be viewed as interconnected subsystems of a single power supply system designed to create a comfortable working environment inside buildings and structures of industrial enterprises.

Manufacturing industrial products is an integrated dynamic system with a set of conflicting factors. Mathematically, a group of functions aimed at modeling the energy factor's impact on the outcome of the enterprise's economic activity can be represented as a multi-criteria optimization problem. A literature review on optimization of heat and power supply at industrial companies demonstrates that there is no conventional solution found to the problem of parameters optimization. The majority of publications (Sennova and Sidler, 1987; Shalaginova, 2018; Krishnan et al., 2016) report on optimization of individual subsystems or their elements. The same approach is exercised in a number of other research studies by Merenkov et al. (1992), Melentiev (1995), et al. According to Clarke (2012), computerized design systems can be utilized to manage the problems of structural engineering. The heuristic multilevel approach to solving problems of mathematical modeling is followed by Sannomiya and Akimoto (1992), Ziębik and Hoinka (2013), Stennikov et al. (2017). In their works, Korelov and Terletskii (2000), Bilenko et al. (2013) and Sviderskii (2013) look at optimization of heat and power supply at industrial enterprises through using automated process control systems. However, particular subsystems and elements being optimized are unable to enhance the efficiency of the enterprise's entire power supply system, since it is an integrated power complex, whose elements and their operating parameters are interrelated, and these links should be taken into account (Zhang et al., 2016).

The abovementioned publications also show differences in approaches to resolving optimization problems. Some studies are based on the energy analysis of systems using the concept of exergy (Chen and Hua, 1996; Kim and Kwon, 1998). In this case, however, researchers ignore economic factors. Technical and economic analysis, which includes both thermodynamic and economic factors, underlies the majority of the papers. Here, we can distinguish between two methods for considering these factors. The first one is a conventional technical and economic method that implies thermodynamic and economic factors to be analyzed successively (Tsatsaronis, 1999). The second one - the thermoeconomic method - is concentrated on thermodynamic and economic factors to be analyzed simultaneously (Querol et al., 2013; Ahmadi et al., 2014). These methods are radically different in the approach to resolving the optimization problem, and, therefore, they can be viewed as two independent techniques. Consequently, parameters of enterprises' heat and power supply systems are feasible to optimize using exergy methods.

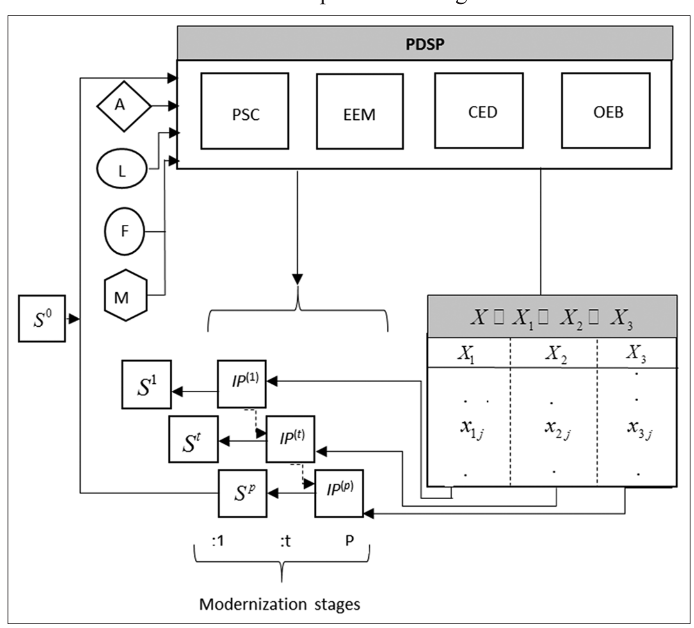
The choice of energy costs as an objective function when optimizing the parameters is predetermined by the largest share of these expenses in running costs (RC) (Somov and Morozov, 1996). Therefore, a comparative modeling of projects with different sets of characteristics should be performed in order to make a managerial decision. This issue will be discussed further in the study.

3. MATERIALS AND METHODS

In the paper, we direct meticulous attention to the issues of rationing and reducing power consumption by industrial enterprises, as well as the problem of balancing the use of various energy sources. We develop a model for enhancing enterprises' energy efficiency that describes the structural and temporal sequence of dealing with the issues under consideration (Figure 1). The increase in enterprises' energy efficiency is based on the analysis of the system's initial parameters (S_0) and represents a multi-stage process (1,…, i,…, p) of a successive change of states (S_1,…, S_i,…, S_p) due to the implementation of integrated projects ($IP^{(1)}$,…, $IP^{(i)}$,…, $IP^{(p)}$). They are initiated using measures to improve the energy efficiency of heat sources (X_1), thermal networks (X_2) and heat consumers (X_3). The procedures for designing and selecting the projects proposed in the current study are applied to develop integrated and elementary projects.

The energy-economic model establishes a quantitative relationship between the indicators of the system's state, RC, operating and design characteristics of enterprises' elements before and after projects implementation, external influences, capital costs (K) incurred in project implementation, account period (n) and project selection criteria:

Figure 1: A conceptual model for enhancing energy efficiency of enterprises engaged in the industrial sector, where S_0, S_1, S_i, S_p are the system's states; 1., i., p denote the stages of the system's improvement; A, F, L and M are aspects of projects' selection, external factors, constraints in the development and selection of projects, operating and design properties representing temporal functions; PDSP denotes procedures for designing and selecting the projects; OEB is overall energy balance; CED is cause-effect diagrams; EEM is energy-economic models; PSC is project selection under constraints; X_1, X_2 and X_3 are simple improvement projects; n(i) is an integrated project at the *i*-th improvement stage



$$A = f(S^i, S^{i+1}, RC^i, RC^{i+1}, M^i, M^{i+1}, F, K, n) \quad (1)$$

Two types of EEMs - elementary and integrated – are being considered. Elementary EEMs display technical and economic features of a single energy-saving process that belongs to one of the enterprise's subsystems. Integrated EEMs allow coordinating the fundamental characteristics of elementary projects that belong to various enterprises' subsystems (a set heating and electrical capacity of machinery and equipment, diameters of central heating network tubes, etc.). The value of fuel equivalent savings is one of the aspects of energy efficiency; it is achieved while switching from one scheme to another provided that power and thermal capacities for consumers are equal.

To assess the interrelation between enterprises' state, heat generation profitability (R) and prices for fuel and energy resources, the following equation is proposed:

$$1 + R = r\left(\eta_k^{br} - q_{tr\ loss}\right) / \left\{k\left[1 + r_e\left(q_{sn} + q_n\right)\right]\right\} \quad (2)$$

The values from equation (2) can be categorized into four groups: Prices for fuel, heat and electricity (c_P, c, c_e, $r = c/c_P$, $r_e = c_e/c_F$); η_k^{br} - q_{sn} heating unit energy efficiency; $q_{tr\ loss}$ - heat losses, electricity costs involved in energy carrier transportation q_n ; coefficient (k) of extra costs incurred in thermal energy generation.

On this basis, we analyze the feasibility of connecting a remote consumer (enterprise) to a centralized thermal power station with idling capacity. The value of annual savings of fuel equivalent ΔB is applied as a criterion of energy efficiency:

$$\Delta B = \Delta b_E - (b_{eltr} \times b_e + b_{fch}) \times Q > 0 \quad (3)$$

Where Δb_e is specific savings of fuel equivalent; E is energy generation per year; b_{eltr} denotes specific electricity losses during energy carrier transportation; b_e is specific losses of fuel equivalent during electricity generation after connecting a remote consumer; b_{fch} refers to specific losses of fuel equivalent associated with compensation of heat losses; Q is heat generation per year.

Establishing the capacity of the base-load (Q_b) and peaking (Q_p) heat sources is implemented using the aggregate costs minimization criterion:

$$Z = k_b Q_b + k_p Q_p + n\left(\frac{E_b c_b a_b}{\eta_b} + \frac{E_p c_p a_p}{\eta_p}\right) \rightarrow min, \quad (4)$$

where k_b and k_p are specific capital costs of the base-load and peaking heat sources; E_b and E_p are the amount of thermal energy per year; c_b and c_p denote the price of the primary energy source in the base-load and peaking state; η_b and η_p are conversion coefficients of the primary energy source used to produce heat; a_b and a_p refer to extra costs coefficients in the base-load and peaking states that show the ratio between total RC and energy-related costs incurred in thermal energy generation; n is account period of a project.

The ratio between capacities Q_b and Q_p is determined by the ultimate temperature of atmospheric air $^oC\ t_i$. If the temperature is above this level, the base-load heat source bears the heating load; if the temperature is below the ultimate level, both base-load and peaking heat sources carry the heating load (Figure 2).

The model justifies the application of combined heat sources with the base-load and peaking units. The base-load heat source is characterized by a high energy efficiency and large initial capital costs, whereas the peaking heat source displays a relatively low energy efficiency and moderate initial capital costs.

Mathematically, the energy-saving problem is defined by formula:

$$E = e_1x_1 + e_2x_2 + \ldots + e_ix_i + e_nx_n \rightarrow \max_{x \in \Delta\beta}, \quad (5)$$

where E is total savings yielded due to energy efficient projects implementation; x_n is project delivery; e_n is specific (delivery-related) annual savings produced through implementing the relevant project.

A set of admissible alternatives $\Delta\beta$ is generated by the following system of constraints in the form of inequations:

$$K1x_1 + k_2 + x_2 + \ldots + k_ix_i + k_nx_n \leq K, \quad (6)$$

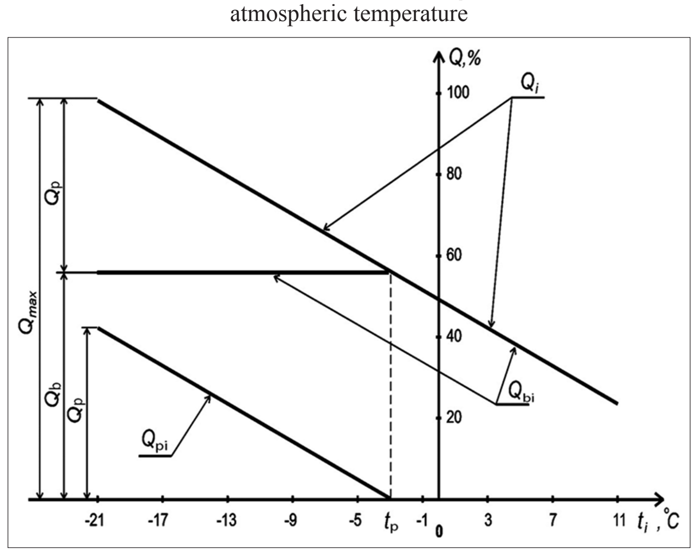
$$x_1 \leq X_1, x_2 \leq X_2, \ldots, x_i \leq X_i, \ldots, x_n \leq X_n \quad (7)$$

$$x_1 \geq 0, x_2 \geq 0, \ldots, x_i \geq 0, \ldots, x_{n \geq 0} \quad (8)$$

where k_n is specific (delivery-related) costs incurred in implementation of the project; X_n denotes the maximum possible project delivery; K is the amount of available resources to be used to implement the whole set of the considered projects.

Formula (5) describes the objective function as total savings generated though projects implementation. Inequation (6) is a financial constraint. Inequations (7) are constraints on delivery

Figure 2: Changes in capacities Q_b and Q_p depending on the atmospheric temperature



of each project, and inequations (8) are obvious conditions of inalienability.

The problem under consideration makes sense if (9):

$$k_1x_1+k_2X_2+\ldots+K_ix_i+K_nx_n>K \quad (9)$$

Inequation (9) means that the amount of resources available is less than the amount of resources needed for implementing all the projects to the full extent.

With a view to enhancing the range of criteria for selecting energy-efficient projects, the economic objective function (5) can be transformed into a comprehensive utility criterion:

$$P = e_1k_1/T_{1av}+e_2k_2/T_2av+\ldots+e_ik_i/T_{iav}+\ldots+e_nk_n/T_{nav}\rightarrow max, \quad (10)$$

where T_{iav} is the average rank of the i-th project based on the criteria p.

$$T_{iav} = (T_{i1}+T_{i2}+T_{i\alpha}+\ldots+T_{ip})/p, \quad (11)$$

where $T_{i\alpha}$ is the rank of the *i*-th project based on the criterion α.

Along with a payback period, the comprehensive utility criterion (10) allows taking into account other effects of a project established using the expert method, e.g. increasing reliability, ensuring energy independence, etc.

Thus, the proposed method allows analyzing the effect of the main factors on comparative technical and economic energy efficiency.

4. RESULTS AND DISCUSSION

Comparative analysis was performed on heat sources based on the total costs criterion among gas heating units; condensing heating units; biofuel heating units; wastewater heating units; heat sources with cogeneration units; heating power units; heating power units with accumulation, and waste heat units.

The share of capital costs significantly differs from total costs for various heat sources; however, the share of RC is dominant for all types of units. Among the above-mentioned heat sources, waste heat units at industrial enterprises, condensing heating and cogeneration units are the most economically efficient in terms of total costs minimization.

The energy-economic model allows comparing the technical and economic aspects of two modernization scenarios of the heat supply system of an industrial enterprise circuit (buildings and other structures): Scenario A implies the replacement of heating units, networks and ancillary equipment, and Scenario B, along with the replacement of the same parts, implies thermal modernization of industrial structures. These two scenarios are compared by the total costs minimization criterion.

The benefits of Scenario B are especially tangible within the range of certain influencing characteristics, such as account period, thermal insulation properties, the specific price of thermal modernization, the price of fuel and energy resources, the length of thermal networks, and other characteristics, whose impact can be studied using the proposed mathematical model. Figures 3 and 4 illustrate the influence of specific heat consumption of industrial buildings under thermal modernization and the length of the thermal network on the capital costs payback period.

Specific heat consumption of industrial buildings varies between 100 and 350 kWh/m^2 (Bashmakov, 2015; Livchak, 2015; Harvey, 2013). In general, actual heat consumption of buildings is below the base level, but it is still significantly higher than the level stipulated in modern regulatory requirements and which is achieved after thermal modernization.

Energy-economic efficiency enhances with increasing heat load, the annual period of thermal energy use and the price of fuel and energy resources, a decreasing length of thermal networks, as well as by choosing the optimal transfer rate of the heat-transfer agent. However, the range of economic feasibility is substantially narrower if compared to the range of energy feasibility. Comparing actual and normalized energy balances makes it possible to evaluate the potential for energy conservation in the thermal circuit of an industrial enterprise and identify priority energy-saving projects.

Conducting a simulation modeling based on performance indicators of Russian companies[1], we calculate economic efficiency based on the assumption that savings achieved and capital costs are directly proportional to project delivery. A wide variety of potential energy-efficient projects is attributed to the opportunity to choose the type of fuel and energy resource and the type of thermal unit. It is also associated with the level of the heat and power supply system centralization, the degree of thermal modernization of industrial buildings and structures. The calculation results are presented in Figure 5.

Heating system nominal capacity is 1000 kW, which allows heating an industrial building of 12000-15000 m^2 in area with average insulation to heat losses 95-105 W/m^2, located in central Russia with a temperate climate. At that, the average return of the heating system during the heating season (200 days a year) will be around 500 kW. For the whole heating season, an industrial enterprise's heating system should generate 2400000 kW*h of heat. For buildings of larger area, there should be a proportional increase in capacity and financial expenses.

In the cold period of the year, during off-hours or if industrial buildings and structures lie idle, a fall in air temperature is acceptable provided that the temperature is normalized before using the building again. To reach the normalized temperature, several hours before using the premises the heat-transfer agent's temperature should be set above the scheduled temperature. The use of premises is regulated by a schedule that can be altered during the year. This allows setting a daily and weekly program for changing temperature in facilities in order to save heat. Thermal

1 Energy Conservation in Russia database. Russian Energy Agency. Available at: http://energy.csti.yar.ru.

Figure 3: Effect of specific heat consumption of industrial buildings under thermal modernization on the capital costs payback period

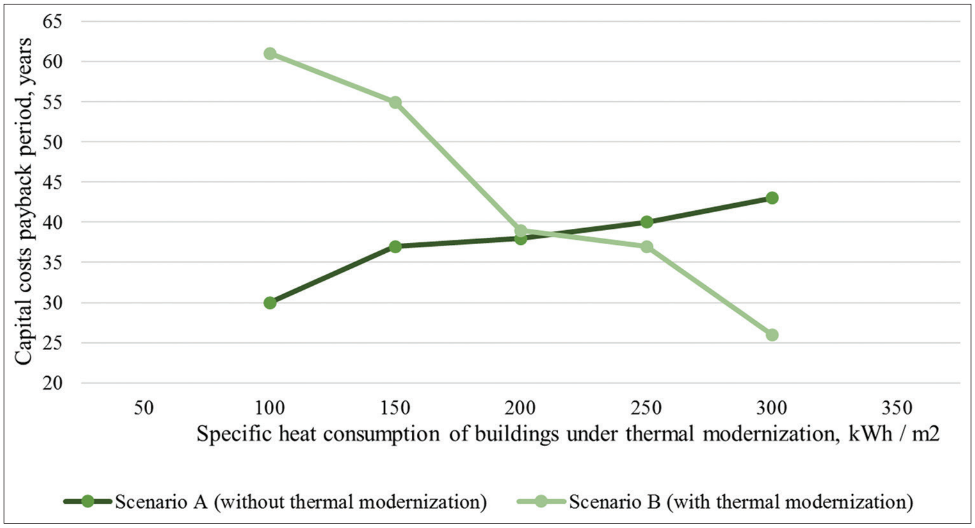


Figure 4: Effect of the length of the thermal network of industrial buildings on capital costs payback period

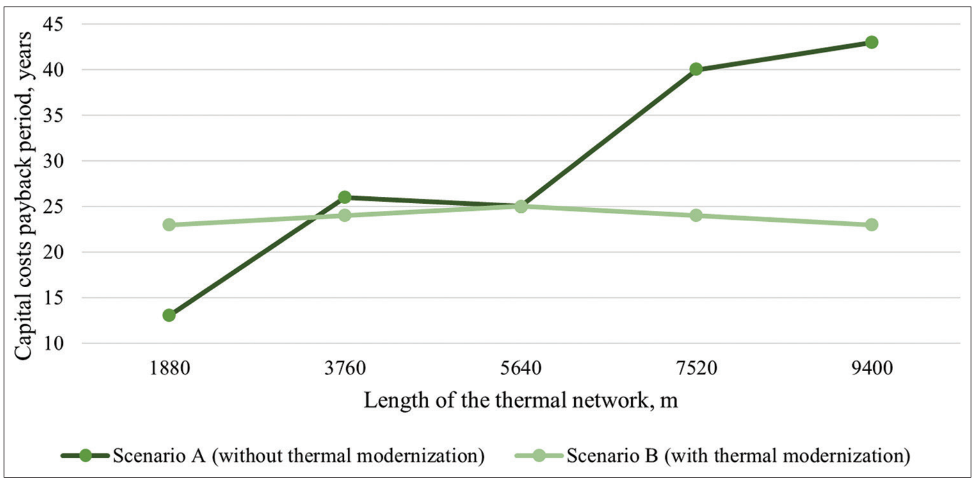
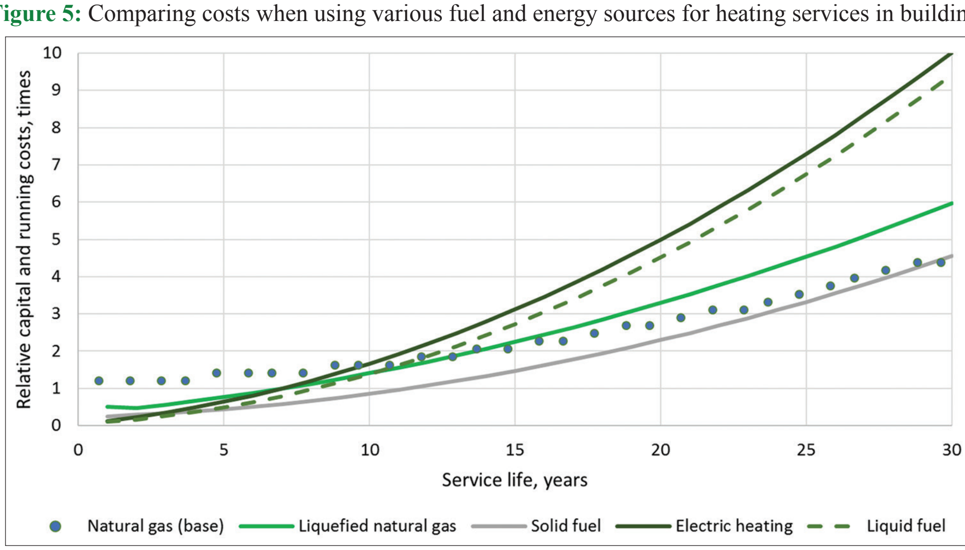


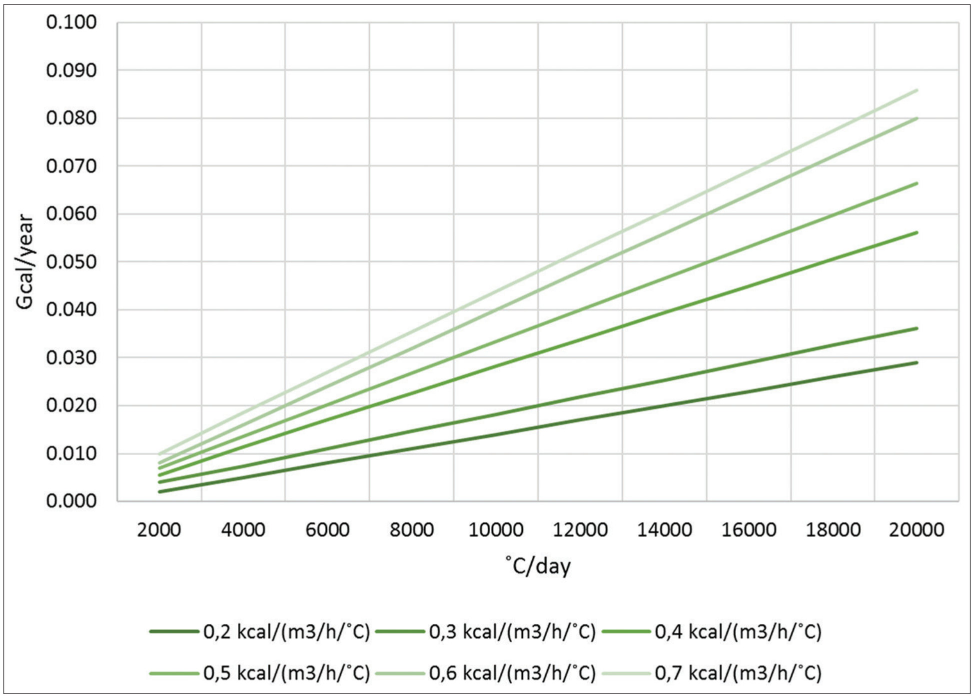
Figure 5: Comparing costs when using various fuel and energy sources for heating services in buildings



inertia in buildings predetermines the duration and the amount of degrees for the heat-transfer agent's temperature to be changed. They can be established both mathematically and empirically.

The energy, economic and environmental effects of setting a daily and weekly program for reducing temperature during off-hours (taken at 12°C) depend on the climatic conditions of the object's

Figure 6: Thermal energy savings under various program modes of temperature change in industrial buildings (1/m³)



location and the specific thermal characteristic of the building (for heating). Figure 6 presents a model calculation of savings in various modes of change in the specific thermal characteristic.

The lines in Figure 6 correspond to buildings with the given specific thermal characteristic from 0.2 to 0.6 kcal/(m^3/h/°C) in increments of 0.1. To produce absolute values, it is necessary to multiply the values obtained by the heated area of the building (m^3).

The estimates prove that the greatest share of fuel savings is due to the implementation of energy-efficient projects in buildings. It is noteworthy that energy-efficient projects in buildings cause a reduction in connected heat load and affect the characteristics of the projects on energy-efficient modernization of heat sources and networks.

At the same time, energy efficiency should not be equated to the economic efficiency of energy consumption (Chemezov, et al., 2015). Even the most energy-efficient project may not prove to be the most cost-effective, since high energy efficiency requires significant investments, and it is not always possible to cover the expenses within a reasonable period. As a rule, high energy efficiency implies sizeable investment, therefore, produced energy savings should be compared with the relevant expenditures. In this case, we can talk about optimal energy efficiency.

5. CONCLUSION

The specificity of energy efficiency in the context of innovation development of industrial enterprises is necessary to be explored with a focus on relevant measures. Energy-related investigation of enterprises and the estimates provided indicate that the largest portion of potential energy savings is attributed to implementation of energy-efficient projects in industrial buildings and structures. Thermal modernization with a profound synergy effect is one of such measures, which makes it possible to reduce connected heat load, the required capacity of heat sources, the scale of the thermal network, energy losses and energy consumption, as well as capital costs incurred in installation of new heat sources and development of networks.

By using the energy-economic model, it is possible to compare the technical and economic aspects of the two modernization scenarios of an industrial enterprise's heat supply system: On the one hand, by upgrading the enterprise's energy facilities, and on the other hand, by upgrading these facilities along with conducting thermal modernization of the buildings and structures. The second scenario produces the results that are not constant and present if there is a certain range of influencing factors. We have established that, if compared with total costs for various heat sources, the share of capital costs differs significantly; however, the share of RC is prevailing for all types of units.

Our calculations show that there is an inverse correlation between specific heat consumption of buildings under thermal modernization and the length of the thermal network. As specific energy consumption within the thermal modernization scenario increases, the payback period of capital costs reduces. The effect of this dynamics is virtually proportional. At the same time, the length of an enterprise's heat circuit (the scale of the network) exerts a minor effect on the payback period of capital costs. Nevertheless, if juxtaposing Scenario A (without thermal modernization), in which the payback increases with the enterprise's growing thermal network, and the integrated Scenario B, the latter exhibits the most substantial savings. Another conclusion of high importance is that the potential for enhancing energy efficiency of thermal modernization of industrial buildings and structures is significantly higher than that for improving energy efficiency of heat sources and networks (the enterprise's heat circuit).

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